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Dimet Laval Nozzle Expansion Section Analysis and Optimization

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Abstract. The cold spray technology mainly accelerates the powder in the Laval nozzle by gas, ensuring that the powder has a greater velocity at the exit of the Laval nozzle, and achieving high-efficiency deposition on the substrate, thereby obtaining a better performance of the deposition coating. The article uses numerical simulation to study the influence of the length of the expansion section of the Dimet Laval nozzle on the acceleration effect of Al powder. The results show that the length of the expansion section of the nozzle is an essential factor affecting the velocity of the Al powder at the nozzle outlet. Through analysis, it can be known that the pressure inlet range of the Dimet Laval nozzle is 1.0 MPa, and the length of the expansion section is about 210 mm, which can ensure that the Al powder has a better acceleration effect in the nozzle and has a better velocity at the nozzle outlet. It is recommended that the joints between the small sections of the nozzle expansion section should be kept as smooth as possible so that the accelerating effect of the accelerating gas on the Al powder is more uniform and stable.

Keywords: cold spray nozzle, turbulence, velocity, Laval nozzle, numerical simulation.

1 Introduction

There are many turbulence models used to simulate the compressible flow inside the Laval nozzle. For example, the S-A turbulence model was proposed by Spalart and Allmaras in 1992. It is believed that the S-A turbulence model is often used for the numerical simulation of large gradient, near-wall gas flow [1]. The k-ε turbulence model is mainly proposed for high Reynolds number flows [2]. Yuan scholars believe that the k-ω turbulence model has a small amount of calculation and the processing of boundary conditions is straightforward [3].

First, the three turbulence models of S-A, k- ε, and k-ω can be compared in terms of convergence velocity, mass flow error, Mach number error, to provide a reference for choosing a turbulence model that simulates the flow of cold spray technology particles in a Laval nozzle [4].

In the simulation of the internal flow channel of the Laval nozzle, the three commonly used turbulence models are the S-A model, k-ε model, and k-ω model.

Yang [5, 6] scholars have shown that the k-ω turbulence model is compared with the S-A turbulence model. The k-ε turbulence model can better represent the flow law of the internal flow channel of the Laval nozzle; compare the residual diagram, the k-ω turbulence model has a better convergence velocity; compare the mass flow error, the k-ω turbulence model has the smallest mass flow error; compare the Mach number Error, the Mach number error of the k-ω turbulence model is the smallest ([(theoretical calculated Mach number-numerical simulation maximum Mach number)/theoretical Mach number × 100 %]). Therefore, the turbulence model is used when simulating the internal flow passage of the Dimet Laval nozzle [4].

Analyze the influence of the length of the expansion section of the cold spray nozzle on the outlet velocity of the powders.

2 Research Methodology

2.1 The governing equation

The compressible two-dimensional axisymmetric flow satisfies the N-S equation in the cylindrical coordinate system [5].

According to this scheme, the angles are calculated by formulas [15]:

$$\frac{\partial Q}{\partial \mathrm{t}}+\frac{\partial E_u}{\partial x}+\frac{\partial F_u}{\partial \mathrm{r}}+\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial r}+\frac{H}{\mathrm{r}}=0 \tag{1}$$

2.2 The turbulence models

The specific description of the turbulence model is as follows:

$$\rho \frac{D\vec{v}}{Dt} = G_v + \frac{1}{\sigma_{\vec{v}}}\left\{\frac{\partial}{\partial x_j}\left[\left(\mu + \rho \vec{v}\right)\frac{\partial \vec{v}}{\partial x_j}\right] + C_{b2}\rho\left[\frac{\partial \vec{v}}{\partial x_j}\right]^2\right\} - Y_v \quad (2)$$

Among them, $\vec{v}$ represents the turbulent motion viscosity coefficient, v represents the molecular motion viscosity coefficient; G_v is the generation term, and Y_v is the destruction term.

k- ε Turbulence Model [6] is as follows:

$$\frac{\partial \rho \kappa r^m}{\partial t} + \frac{\partial \rho u_u \kappa r^m}{\partial x} + \frac{\partial \rho_v \kappa r^m}{\partial r} = \frac{\partial}{\partial r}\left[\frac{\mu_t r^m}{\sigma_k}\frac{\partial \kappa}{\partial r}\right] + r^m\left(P\kappa - \rho\varepsilon\right) \quad (3)$$

$$\frac{\partial \rho \varepsilon r^m}{\partial t} + \frac{\partial \rho u \varepsilon r^m}{\partial x} + \frac{\partial \rho v \varepsilon r^m}{\partial r} = \frac{\partial}{\partial r}\left[\frac{\mu_t r^m}{\sigma\varepsilon}\frac{\partial \in}{\partial r}\right] + r^m\left(C_1 P\kappa - C_2\rho\varepsilon\right)\frac{\varepsilon}{\kappa} \quad (4)$$

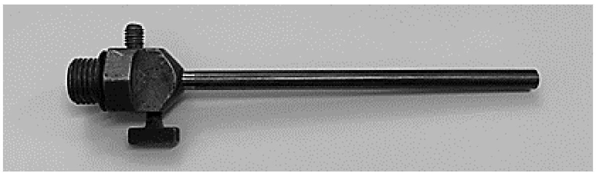
Also, the k-ω Turbulence Model [6] is as follows:

$$\frac{\partial \rho \varepsilon r^m}{\partial t} + \frac{\partial \rho u \omega r^m}{\partial x} + \frac{\partial \rho v c \omega r^m}{\partial r} = \frac{\partial}{\partial r}\left[\frac{\mu_t r^m}{\sigma_k}\frac{\partial \in}{\partial r}\right] + r^m\left(P\kappa - C_D\rho\kappa\omega^{0.5}\right) \quad (5)$$

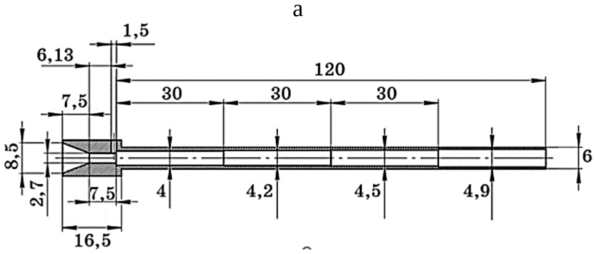
$$\frac{\partial \rho \varepsilon r^m}{\partial t} + \frac{\partial \rho u \omega r^m}{\partial x} + \frac{\partial \rho v \omega r^m}{\partial r} = \frac{\partial}{\partial r}\left[\frac{\mu_t r^m}{\sigma_k}\frac{\partial \in}{\partial r}\right] + r^m\left(C_1 P\kappa - C_2\rho\kappa\omega^{0.5}\right)\frac{\omega}{\kappa} \quad (6)$$

2.3 Experimental setup

The cold spray Dimet Laval nozzle is used is to be chosen, as shown in Figure 1 a, and the detailed design parameters of the Dimet Laval nozzle are shown in Figure 1 b [7]; After that, the internal flow channel of the Dimet Laval nozzle is obtained by 3D modeling software. The gas inlet of the Dimet Laval nozzle and the inlet of Al powder are perpendicular to each other, and the powder inlet is located at the throat of the Dimet Laval nozzle.



a



b

Figure 1 – Dimet Laval nozzle (a) and its design parameters (b)

Many technical parameters affect the gas and powder flow velocity in the Dimet Laval nozzle, such as temperature (powder, gas, or substrate), powder size, spraying distance, gas pressure, Laval nozzle structure. Tan summarized the influence of technical parameters on cold spray technology [8–10]. The length of the expansion section of the Dimet Laval nozzle is an essential factor that affects the acceleration of the powders in the Dimet Laval nozzle. If the expansion section is too short, it will not accelerate the powders in the Dimet Laval nozzle fully. If the expansion section is too long, there will be possible that the powder has already begun to decelerate in the Dimet Laval nozzle; therefore, it is essential to research the influence of the length of the expansion section on the velocity of the powder at the nozzle outlet.

In the article, the pressure inlets are 0.8 MPa, 1.0 MPa, and 1.2 MPa, and the length of the expansion section of the Dimet Laval nozzle is 120 mm, 150 mm, 180 mm, 210 mm, and 240 mm. The velocity distribution of Al powder at the outlet of Dimet Laval nozzle is researched. The gas is air, the total inlet temperature is 900 K, and the powder is made of spherical Al powder with a diameter of 25 μm.

3 Results

3.1 Analysis of Al powder velocity at the same pressure

Solidworks simulate the velocity distribution of Al powder in the Dimet Laval nozzle. Firstly, research the velocity distribution of the Al powder in the expansion section of the Dimet Laval nozzle with different lengths under the same pressure inlet; secondly, research the velocity distribution of Al powder in the nozzle at different pressure inlets of the expansion section of the Dimet Laval nozzle of the same length.

Analyze the expansion section of different lengths under the same pressure inlet conditions, the acceleration of the Al powder in the Dimet Laval nozzle, and the velocity at the nozzle outlet; respectively simulate the pressure inlets at 0.8 MPa, 1.0 MPa, and 1.2 MPa; As shown in Figure 2, the pressure inlet is 0.8 MPa, and the velocity distribution of Al powder in the expansion section of different lengths.

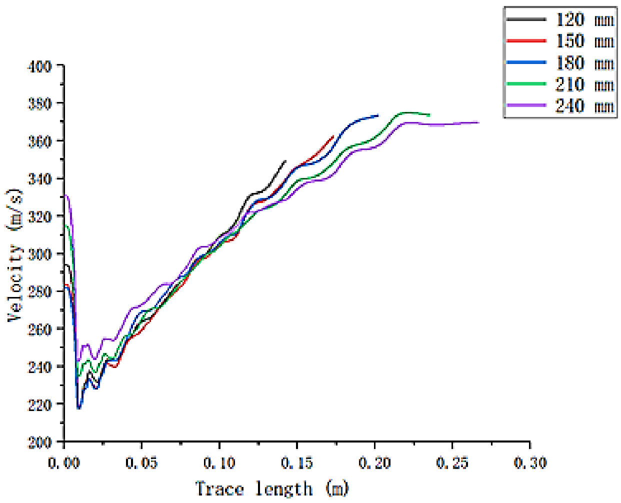
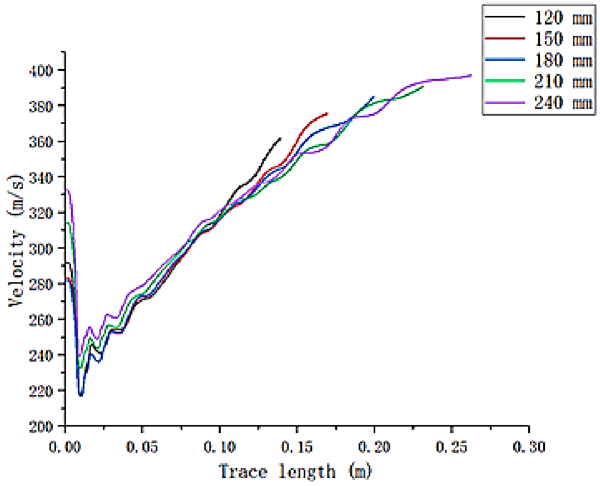


Figure 2 – The pressure inlet is 0.8 MPa, the velocity distribution of Al powder in the expansion section of different lengths

It can be seen from Figure 2 that when the pressure inlet is 0.8 MPa, the Al powder has been accelerated near the expansion section of the nozzle 220 mm, so the expansion section length is 120 mm, 150 mm, and 180 mm nozzles, the Al powder is still in a state of acceleration before the nozzle exit.

Expansion section length of 210 mm and 240 mm nozzles, Al powder, has been accelerated before the nozzle exit, and the Al powder decelerates in the nozzle; five different lengths of expansion section nozzles, The Al powder has reached the critical velocity of spraying, which can meet the deposition on the substrate.

As shown in Figure 3, the pressure inlets are 1.0 MPa and 1.2 MPa, respectively, and the velocity distribution of Al powder in the expansion section of different lengths.



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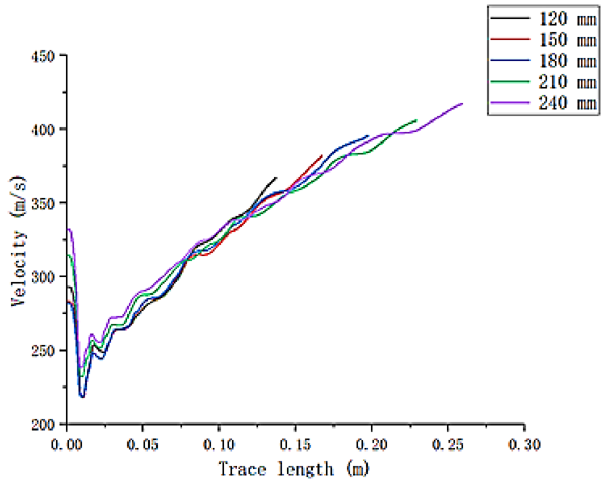


b

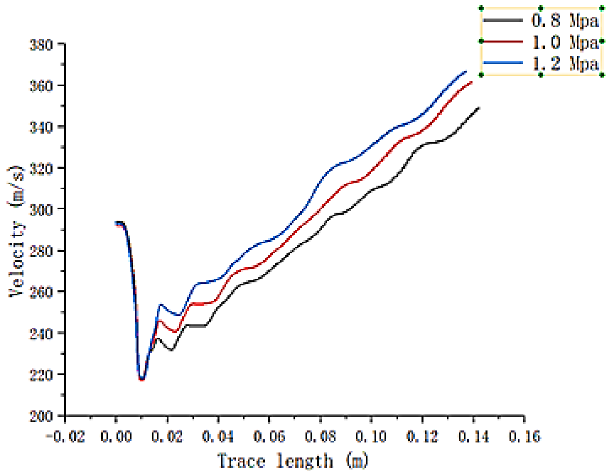
Figure 3 – The pressure inlets are 1.0 MPa (a) and 1.2 MPa (b), the velocity distribution of Al powder in the expansion section of different lengths

Figure 3 a shows that when the pressure inlet is 1.0 MPa. For nozzles with an expansion section length of 120 mm, 150 mm, 180 mm, and 210 mm, the Al powder is still accelerating in the nozzle; for nozzles with an expansion section length of 240 mm, the velocity of Al powder in the nozzle slowly stabilizes. In Figure 3, the curvature of the curve represents the acceleration of the Al powder. Combined with the curvature analysis of the five curves, as the length of the expansion section increases, the curvature gradually becomes smaller, indicating that the acceleration of the Al powder inside the nozzle becomes smaller as the length of the expansion section increases.

It can be seen from Figure 3 b that when the pressure inlet is 1.2 MPa, the Al powder in the nozzles of the five different length expansion sections is still accelerating. This is because the pressure inlet is increased. Combined with the five curves in Figure 3 b, it can also be seen that as the length of the expansion section increases, the curvature gradually becomes smaller, indicating that the acceleration effect of the Al powder in the nozzle is gradually weakened.

3.2 Analysis of Al powder velocity in the same expansion section length

Under the condition of equal expansion section length, analyze the inlet of the different pressure, the acceleration of Al powder in the Dimet Laval nozzle, and the velocity at the nozzle outlet; through simulation, the expansion section length of the nozzle is 120 mm, 150 mm, 180 mm, 210 mm, and 240 mm the Al powder velocity distributions. As shown in Figure 4, the velocity distribution of the Al powder in the nozzles of the expansion section of different lengths when the pressure inlets are 0.8 MPa, 1.0 MPa, and 1.2 MPa.



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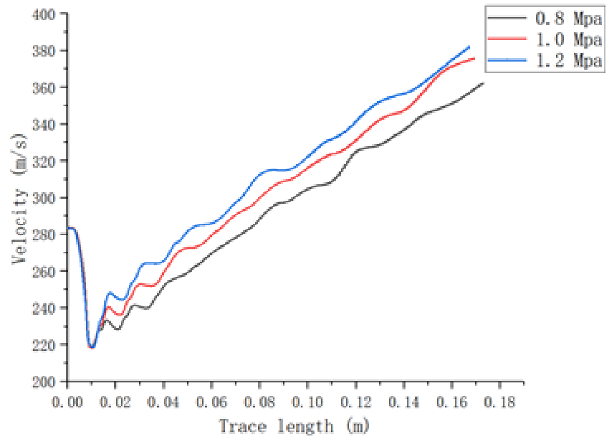

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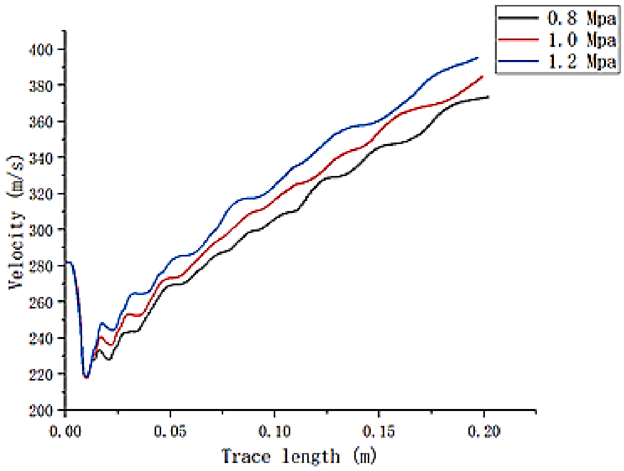

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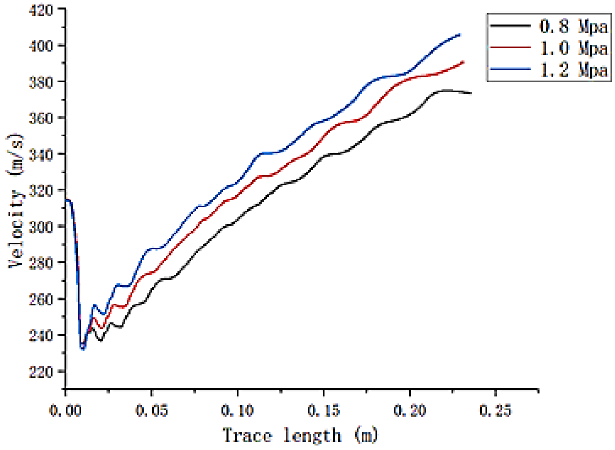

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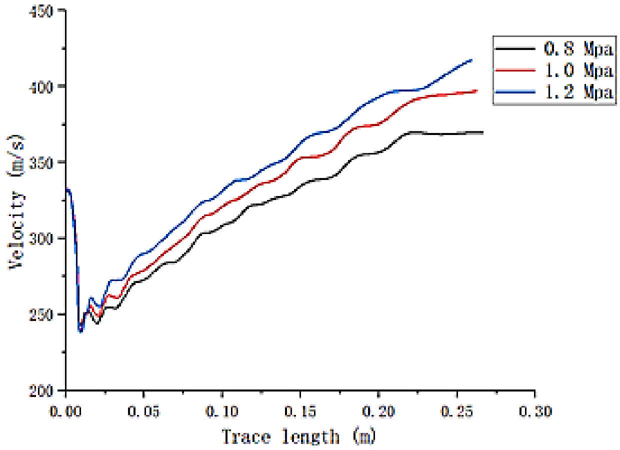

e

Figure 4 – The length of the expansion section is 120 mm (a), 150 mm (b), 180 mm (c), 210 mm (d), and 240 mm (e), the Al powder velocity distribution under different pressure inlets conditions

From Figures 4 a–c, the pressure inlets are an essential factor determining the velocity of Al powder acceleration in the nozzle. The higher the pressure inlet, the shorter the acceleration time of the Al powder; the expansion section the length of the Al powder is also an influencing factor that affects the acceleration velocity of the Al powder in the nozzle.

The expansion nozzle is within a specific length range. As the length of the expansion section increases, the faster the Al powder can obtain in the nozzle.

It can be seen from Figures 4 d–e, when the length of the expansion section of the nozzle reaches a particular value, the acceleration effect of Al powder is reduced; The expansion nozzle of the same length can improve the acceleration effect of the Al powder in the nozzle, and can appropriately increase the pressure inlet. When the pressure inlet is 0.8 MPa, the velocity of Al powder in the nozzle increases first and then decreases; when the pressure inlet is 1.0 MPa, the acceleration effect of Al powder in the nozzle is weakened. By comparing the slopes of all the velocity curves in Figure 4, as the length of the expansion section increases, the curvatures of the different pressure curves have been decreasing, indicating that the acceleration effect of Al powder is gradually weakening.

Therefore, the pressure inlet is too small, and the nozzle expansion section is too short, which is not conducive to the acceleration of the Al powder in the nozzle.

It is essential to choose the proper length of the expansion nozzle in the proper pressure range; increasing the pressure inlet to increase the velocity of the Al powder or increasing the expansion section length to obtain a more significant outlet velocity will increase the spraying cost. Therefore, in the pressure inlet range of 1.0 MPa, the length of the expansion section of the nozzle is about 210 mm, which can ensure that the Al powder has a better acceleration effect in the nozzle and has a good exit velocity at the nozzle outlet, to ensure smooth completion on the substrate deposition.

4 Conclusions

The length of the Dimet Laval nozzle is an essential factor affecting the Al powder outlet velocity. Therefore, a better Al powder outlet velocity can be obtained by changing the length of the expansion section of the Dimet Laval nozzle.

Through analysis, the pressure inlet range of the Dimet Laval nozzle is 1.0 MPa, and the length of the expansion section is about 210 mm, which can ensure that the Al powder has a better acceleration effect in the nozzle has a better exit velocity at the nozzle outlet.

Dimet Laval nozzle expansion section is divided into four parts in total. Each part is 30 mm; it is recommended that the joint between each part be rounded so that the accelerated gas will not produce excessive gas backflow at the joint. This ensures that the velocity of the gas in the entire nozzle remains uniform and stable, thereby ensuring that the velocity of the sprayed material has a better acceleration effect.

5 Acknowledgments

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