

Optimization of Copper Particles Deposition Using Cold Spray Process

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ABSTRACT: This paper describe a detailed study of various parameters, namely applied gas pressure, gas temperature, size of copper particles and dimensions of the nozzle on the outlet velocity of the copper particles. A model of a two – dimensional axisymmetric MOC nozzle was used to generate flow field of copper particles with the help of a gas stream flow at supersonic speed. ANSYS FLUENT software was used for the simulation of a Cold Spray nozzle (MOC). A standard K – ϵ model has been used to account for a turbulence produced due to very high velocity flow. Differences in velocity of copper particle were modeled over the range of applied gas pressure, gas temperature and size of copper particles. From the CFD simulation result optimum values of gas pressure and temperature were found for making a successful coating of copper particles. The optimum nozzle dimensions were also found for the copper particles.

KEYWORDS: C-D nozzle, Copper Particle, Particle Velocity, Particle Temperature and Flow Field.

I. INTRODUCTION

Cold spray is an all solid- state process, thus making it suitable for the deposition of oxygen-sensitive materials such as aluminum, copper, Nickel, etc for temperature sensitive materials such as nanostructured and amorphous powders. It is a coating deposition method that uses a moderately heated, supersonic velocity gas stream to propel relatively cold (i.e., below melting point) particles at a substrate. Upon impacting the substrate the particles undergo plastic deformation and bonding to form a uniform coating surface. The deposited coatings have a high density (e.g., very low porosity) and residual compressive stresses. The cold spray coating process is useful for many applications. For instance, it can be used to apply coatings for wear and corrosion resistance, to repair and restore components, and to incorporate electromagnetic interference shielding onto a part. Metallic powders are most often used as the coating material; however ceramic particles if combined with more ductile particles can be used as well. Zinc, Aluminum, Nickel, Copper, Tungsten Carbide-Cobalt, and Tungsten Copper are some examples of coating materials used for the cold spray process. Cold spray coating was designed to apply a protective coating for improved corrosion resistance while meeting electrical property requirements.

A. Basics of principles

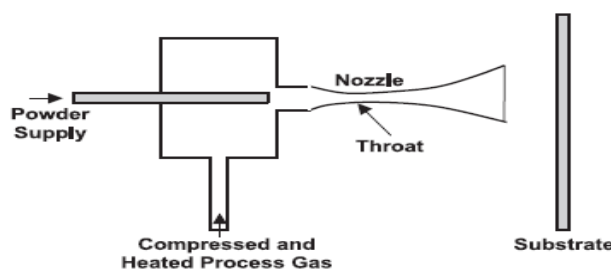


Fig1. Schematic diagram of cold spray apparatus

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Traditional thermal spray coating methods (plasma, electric arc, HVOF) require high temperature of material particles to adhere to a surface. Typically this temperature exceeds the material melting point thereby creating problems inherent in thermal spray. The schematic representation of cold spray apparatus is as shown in the fig.1. In cold gas dynamic spray - high temperatures are not required. This is what makes the technology unique. This technology utilizes the surface interaction of particles moving at supersonic velocities between Mach 2-3 (required velocity is dependent upon application and gas carrier). Since high temperatures are not required in cold gas dynamic spray, adhesion and porosity are superior to thermal spray. Cold-sprayed coatings can be processed with very low numbers of defects and low oxygen contents, and therefore exhibit bulk like properties with respect to electrical or thermal conductivity that are not attainable by normal thermal spray processes.

II. RELATED WORKS

H. Fukunuma, N. Ohno [3]: Helium gas produced much higher adhesive strength than nitrogen and that the strength of the deposits produced by using both helium and nitrogen gases were almost proportional to the chamber pressure. The adhesion produced by cold spray processes appeared to be dependent on the combination of hardness of powder and substrate metals. D. L. Gilmore, R. C. at. [4]: Deposition efficiencies of up to 95% were achieved. The critical velocity for deposition was determined to be about 640 m/sec. V.F. Kosarev, S.V. Klinkov [12]: Investigation of coating formation process from mechanical mixture of metal and ceramic particle allows, due to controlling relation between two competitive processes (erosion and deposition), better understanding of nature of cold spray. Deposition efficiency dependence upon ceramic concentration and dispersion in initial mixture is obtained. The data obtained shows evidence of deposition efficiency increase possibility of mixed powders compared to powder of single metal under proper circumstances. Masahiro Fukumoto, Hiroki Terada [13]: To improve the deposition efficiency of copper fine particles mean diameter around 5mm onto metallic substrate surface in cold spray process, optimization in nozzle design was performed by numerical simulation. P. Mulligan, J. Smith, and J. Stokes [15]: The final design involved modifications to a HVOF thermal spray gun to suit the cold spray process. This was done by producing a de Laval type nozzle that could insert into the gun and application of heat to the exterior of the nozzle using a band heater. Coatings were produced using an external powder injector into the flow of compressed air. Yu Zou [21] Cold spray is a relatively new coating technology in which coatings are produced by spraying metal powders at high velocity, generating bonding through severe plastic deformation at temperatures well below the melting point of the powders.

III. DESIGN OF NOZZLE USING METHOD OF CHARACTERISTICS

A **nozzle** is a device designed to control the direction or characteristics of a fluid flow (especially to increase velocity) as it exits (or enters) an enclosed chamber or pipe via an orifice.

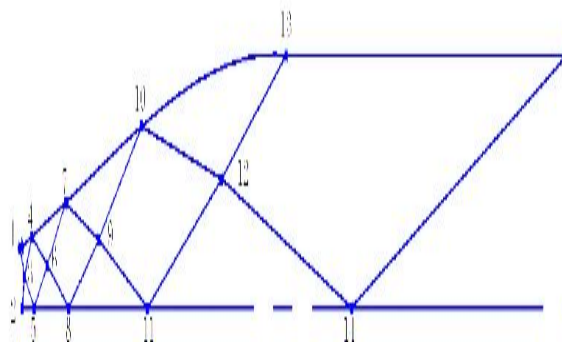


Fig.2 Characteristics mesh of supersonic counter

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Table – I Dimensions of nozzles used for simulation

S.No	Dimension	Air&Nitrogen	Helium
1	Inlet diameter	15mm	20mm
2	Convergent length	13.66mm	16.1mm
3	Throat diameter	2mm	2mm
4	Divergent length	35.9mm	48.22mm
5	Outlet diameter	9mm	9.2mm
6	Barrel Length	144.1mm	131.78mm

Fig.2 shows the nozzle design which was done using the method of characteristics and in the Table-I the dimensions for nozzle used for simulation is represented.

IV. NUMERICAL SIMULATION

GAMBIT 2.3.16 and **Fluent** package was used to model the 2D axis symmetric convergent-divergent (CD) nozzle. Modeling, mesh generation, mesh quality, boundary conditions and allocation of fluid were done in Gambit environment. Computational domain was meshed using regular and structured quadrilateral elements of 70450 shown in fig.3. The governing equations for gas flow include the physical laws of conservation of mass, momentum and energy. The realizable k-ε turbulence model was adopted under gravity. The governing equations were solved with the second order, upwind scheme. The accelerating and heating of particles were computed using the discrete phase modeling (DPM) of FLUENT. The interaction of particles with the gas flow was considered.

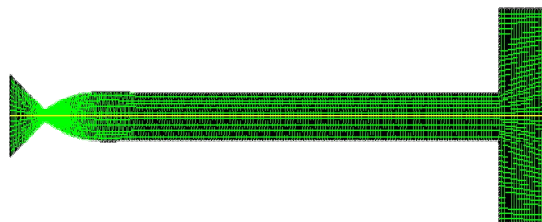


Fig.3 Meshed nozzle for simulation with substrate

V. RESULTS AND DISCUSSIONS

In this section the results of a simulation of gas flow inside the nozzle and the effect of different parameters on the velocity of copper particles are presented.

A. Effect of pressure and temperature on velocity of gas

The figures below shows the velocity of air, nitrogen and helium at the nozzle exit when an applied gas pressure ranging from 30, 36.732 and 38 atm was used to create the flow field. The stagnation temperature varies from 300 k to 700 k.

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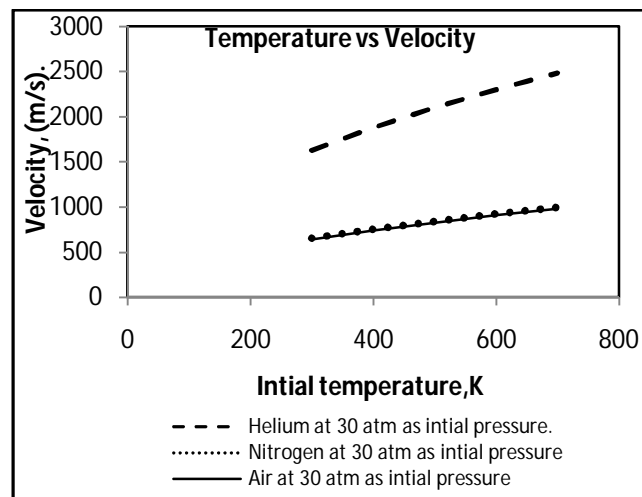


Fig.4 (a).Effect of temperature and exit velocity

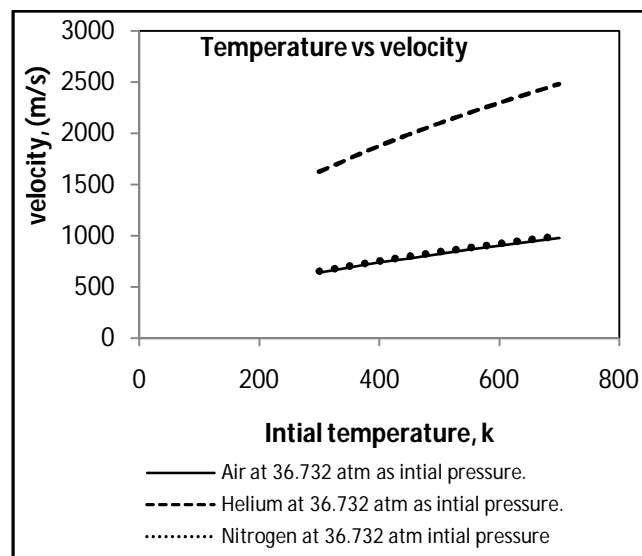


Fig. 4(b) Effect of temperature and on exit velocity when applied gas pressure was 36.732atm

As the above simulation results show a fig. 4(a) to 4(c), the velocity of air, nitrogen and helium increase with increase in stagnation temperature from 300 k to 700 k but an applied gas pressure varying from 30, 36.732 and 38 atm did not affect the exit velocity.

With the nozzle used in simulations, helium attains a higher Mach number than air and nitrogen. For air and nitrogen the specific heat ratio is 1.4 and for helium the specific heat ratio is 1.67. The specific gas constants for air, nitrogen and helium are 287.4 J/Kg K, 296.8 J/Kg K and 2,077 J/Kg K respectively. A conclusion from this is that at the same gas conditions, helium will attain a higher gas velocity than air or nitrogen. Also by increasing the inlet gas temperature the gas velocity will increase and hence result in a higher particle velocity. An increase in gas pressure increases the gas density creating more drag force on the particles which results in a higher particle velocity.

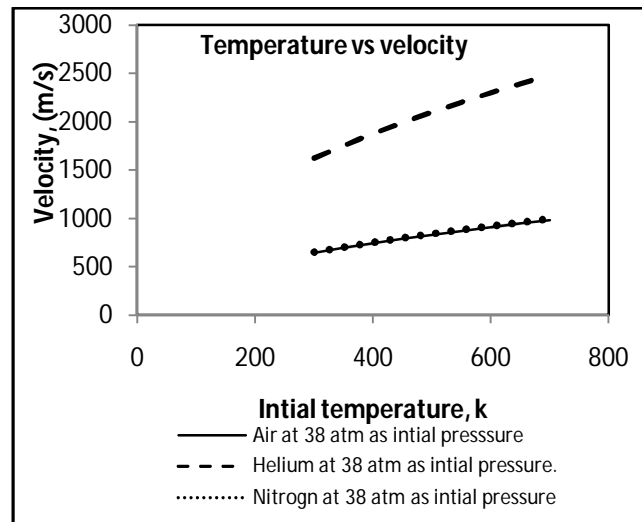


Fig. 4(c) Effect of temperature and on exit velocity when applied gas pressure was 38 atm

The CFD simulation results using the section above of gas parameters shows that helium is a better accelerating gas than air and nitrogen and can be used for cold spraying. However it should be kept in mind that helium is more expensive than nitrogen.

B. Effect of copper particle size on exit velocity

The lot of previous study on cold spraying showed that density and size of the particles have a significant effect on velocity. In the simulation a copper particle size ranging from 5 μm to 100 μm was used and air, nitrogen and helium as carrier gases were the accelerant.

As the CFD results show, smaller particle attain more velocity than larger size particle. At the same the carrier gases, helium has highest particle velocity compare to air and nitrogen at same pressure and temperature of 36.732 atm and 600 k. It was notable that the particle velocity increased significantly when the particle size was decreased. Particle in the size range from 5μm to 40μm attain a higher velocity than large copper particles. It is also interesting to note that the kinetic energy corresponding to the critical velocity for the bonding is much below that required for heating and complete melting of the particle due to plastic dissipation. The later velocity V_m , can be worked out by considering the following simple energy – balance relationship.

$$V_{crit} (d_p T_p) = \frac{\sqrt{657000 - 600 * T_p}}{d_p^{0.18}} a \quad (1)$$

Where;

- d_p = Diameter of particle.
- T_p = Temperature of particle.

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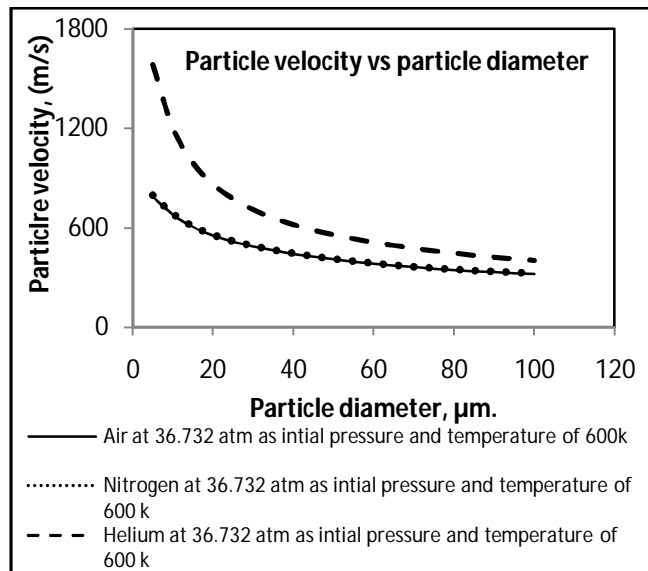


Fig .5 Effect of particle size on its velocity

As shown in figure 5 the critical velocity is approximately half of the velocity required to cause complete melting of the particle. This means that the kinetic energy required for bonding.

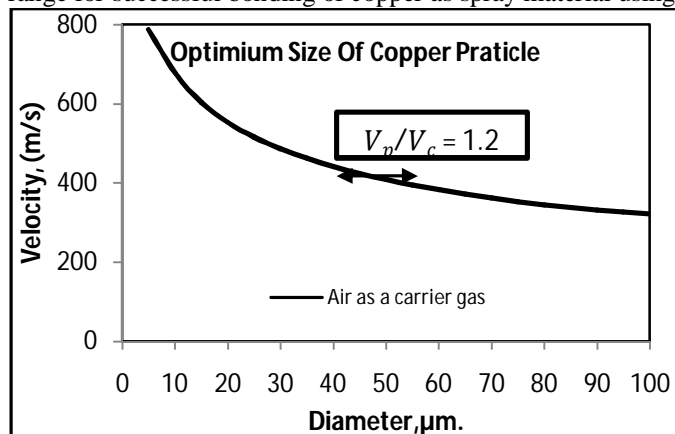
C. Optimization of copper particle

Optimization is the process achieving the perfect result with changing the input parameters like pressure, temperature, particle diameter and type of gas using the same nozzle geometry after comparing all the result we choose the optimum one for the designed nozzle for spraying process.

Now we are going to optimize the diameter for copper particle using the three different gases with the same initial pressure and temperature 36.732 atm and 600 K. Fig.6 (a), 6(b) and 6(c) shows the range of optimum size of copper particle 5μm to 50μm has highest velocity, while using air as a carrier gas.

If we compare the fig 6(a), 6(b), and 6(c) we came to know helium gas have the longer optimum range compare with air and nitrogen. According velocity criteria helium is the best carrier copper particle, but also for other materials before finalizes we want make sure the temperature criteria for optimum particle.

Figure 6(a) Optimum size range for successful bonding of copper as spray material using air as a carrier gas



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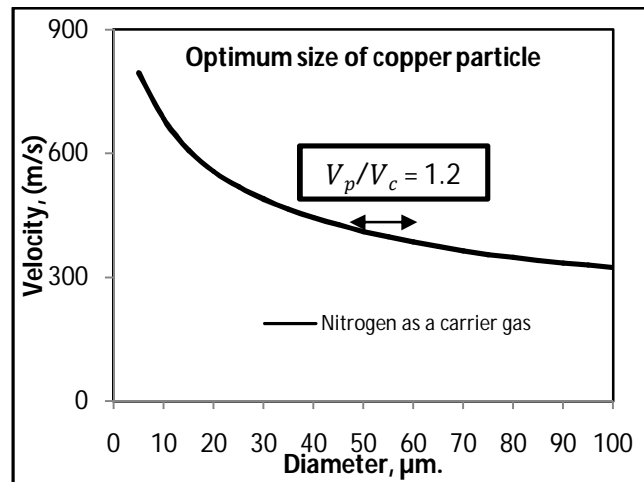


Fig.6 (b) Optimum size range for successful bonding of copper as spray material using nitrogen as a carrier gas

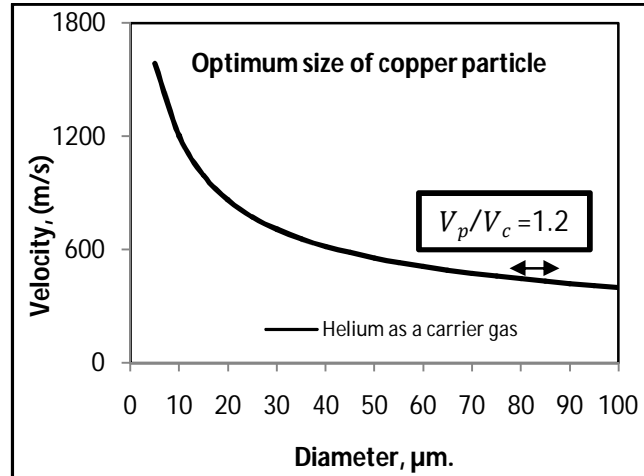
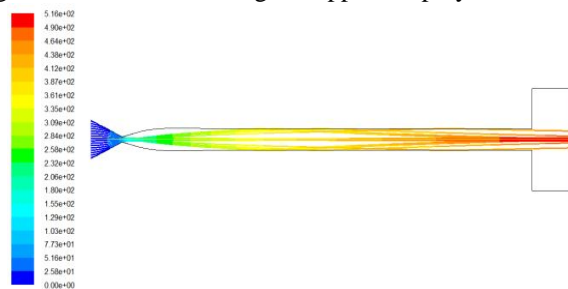


Fig 6(c) Optimum size range for successful bonding of copper as spray material using helium as a carrier gas



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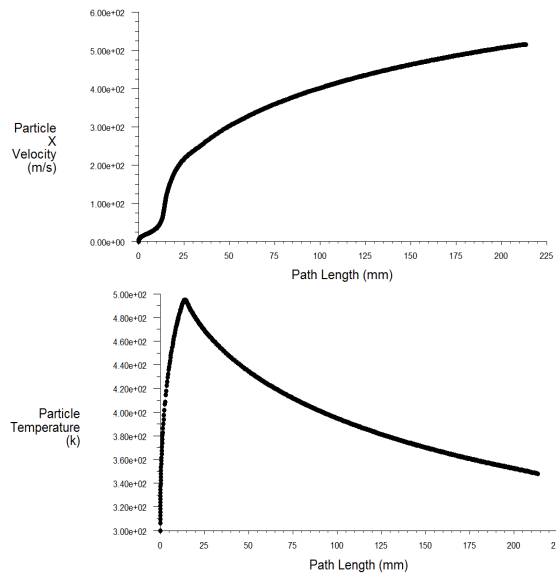
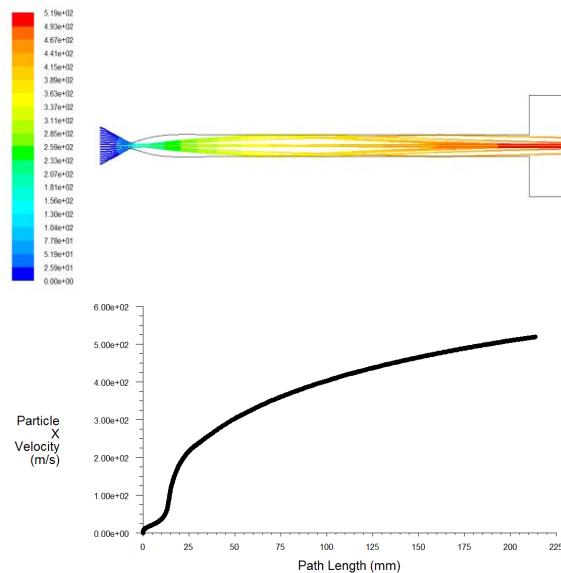


Fig. 6(d) Flow pattern of copper particle 25 μ m and particle velocity and temperature along the nozzle axis using air as a carrier gas



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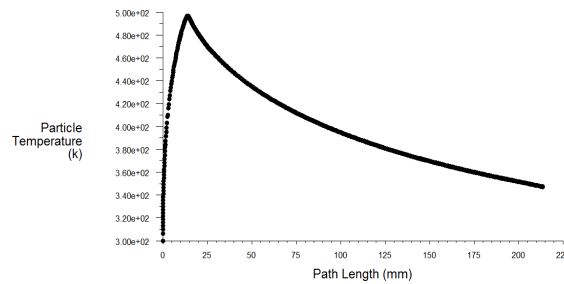


Fig 6(e) Flow pattern of copper particle 25 μ m and particle velocity and temperature along the nozzle axis using nitrogen as a carrier gas

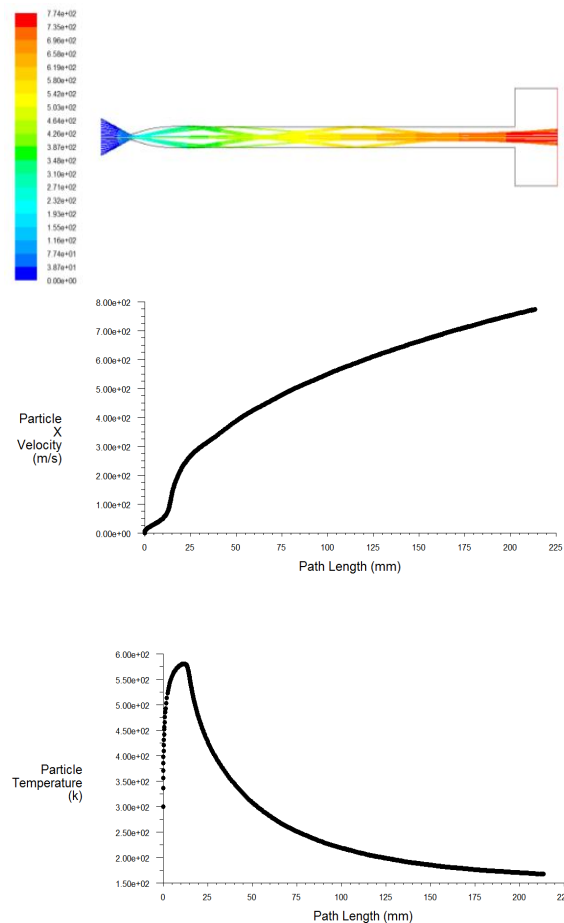


Fig 6(f) Flow pattern of copper particle 25 μ m and particle velocity and temperature along the nozzle axis using helium as a carrier gas

In cold spray, optimization of spray particle is the important role for achieving the higher deposition efficiency. In figure 6(d), 6(e), and 6(f) shows the simulation result for different carrier gas like air, nitrogen and helium, if we compare the above three graphs we came to know helium have higher velocity and lower temperature

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compare with air and nitrogen. So air and nitrogen are better carrier gas compare with helium. Helium is very costly compare to air and nitrogen.

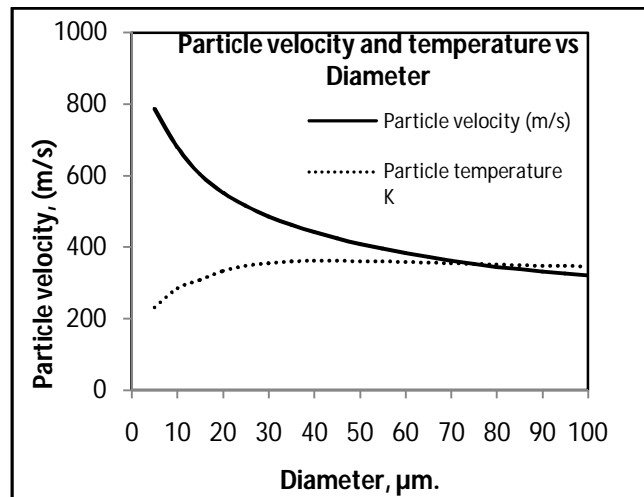


Fig 6(h) Influences of the particle diameter on the velocity and temperature of the copper particle using air as a carrier gas

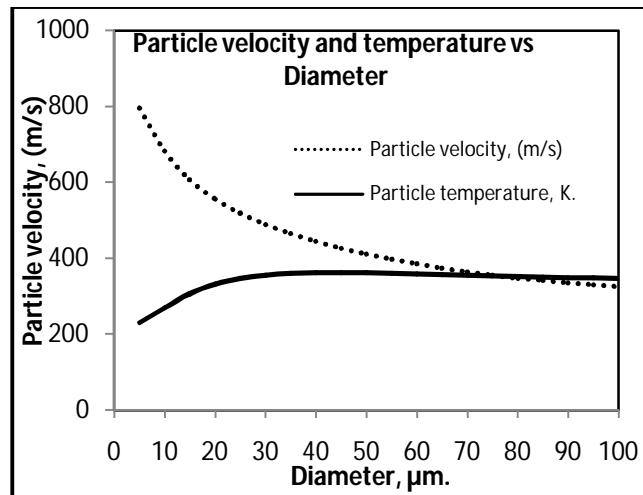


Fig.6 (i) Influences of the particle diameter on the velocity and temperature of the copper particle using nitrogen as a carrier gas

Fig.6(h), 6(i) and 6(j) shows the simulation results of particle temperature attains a maximum value at a particle size of 5 μm and decreases with an increase in the copper particle size. The above results show the relationship for heat transfer between the gas phase and the particle phase. The results show that when air, nitrogen and helium was used for spraying the copper particle, with applied pressure of 36.732 atmand initial temperature 600 k, the air, nitrogen and helium gas temperature at the nozzle exit was 358 k, 358 k and 174 k for 25 μm respectively. This shows the copper particle were at a higher temperature in the beginning the divergent section of the nozzle, while approaching the exit of nozzle, the particle temperature decreased but remained higher than the gas temperature.

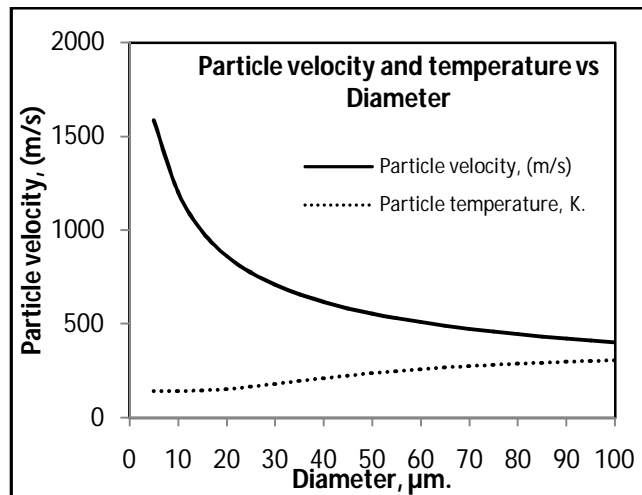


Fig 6(j) Influences of the particle diameter on the velocity and temperature of the copper particle using helium as a carrier gas

Based on the results presented above, increasing the gas temperature increases the particle velocity significantly, which is required for reaching the critical velocity. Gas temperature also influences the temperature of the copper particles and can help particles to deform after striking the substrate.

VI. CONCLUSIONS

Based on the simulation result, it was found that the designed and optimized nozzle geometry was suitable for spray the particle size of 5μm to 50μm copper particle, but not only for the copper particle it's suitable for other ductile material also. While the simulation we saw the thermodynamic result it's acceptable for the cold spray process using that result we choose the optimum carrier gas for the nozzle. And with help of carrier gas result we can get the optimum particle size for the spray for getting higher deposition efficiency.

- ❖ The Mach no of the gas increase with a decrease of pressure along the axis of nozzle. This result in greater gas velocity towards the nozzle exit.
- ❖ The result show that by increasing the gas temperature the gas velocity increases more significantly than the gas pressure, which shows that the gas velocity is function of gas temperature and not the gas pressure.
- ❖ The result shows that the size of copper particles influences the exit velocity of particles. As the copper particle size increased from 5μm to 100μm their velocity decreased.
- ❖ In this simulation air, nitrogen and helium were used for spraying copper particle. Result show that helium is a far better carrier gas because particles achieve a much higher velocity when helium Nozzle is used for spraying. But we can only use helium for larger particle according to window deposition.
- ❖ The temperature of the gas influences the particle velocity of copper particles because the density of gas decrease with increasing gas temperature and hence there is a greater gas velocity to accelerate the copper particle.
- ❖ Increasing the applied gas pressure increase the gas density of gas which results in more drag on the particles, but increasing pressure does not significantly affect the particle velocity.
- ❖ That the result shows the divergent should be very long to achieve the higher velocity.

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