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CALCULATION OF THE CRITICAL VELOCITY OF LOW PRESSURE COLD SPRAYED MATERIALS

1. Introduction

In order to offer a relation between the particles velocity and the deposition efficiency of material powders, researchers offer the concept of critical velocity which is estimated with semi-empirical and numerical methods, and with the relation with the localization of shear instabilities within the materials [6,7,8,10]. The critical velocity, generally depends on the thermal and mechanical properties of materials, for this reason for the calculation of the critical velocity of materials, it should be taken into account the temperature of the particles when impacting the substrate. In order to experimentally determine the critical velocity of a material, the particles velocity is firstly calculated for a powder distribution and then compared to the values of deposition efficiency. This is done in order to yield the size and velocity of the largest particles capable of adhering the substrate. The velocity of the largest particles (the slowest), is generally considered to be the critical deposition velocity [6]. There are four different approaches for calculating the critical deposition velocity theoretically:

1. *Comparing the Rebound Energy against the Adhesion Energy.* Wu in [1] shows that the kinetic energy of the particles is dissipated during plastic deformation; other part of the energy is stored in the elastic zone during loading and is recovered when unloading. By this means a model is created where the rebound energy "R" of a material is compared to the adhesion energy “A” of the material. The velocity where the adhesion energy is higher than the rebound energy A>R is considered the critical adhesion velocity.

2. *Calculating if a Shear Instability Occurs during deformation via finite difference model.* Grujicic in [2] uses a simple finite difference model in order to calculate the flow stress of the material during deformation and the material softening caused by heat release; using the data obtained from the model, the velocity at which a shear instability happens can be determined.

3. Calculating if a Shear Instability occurs during deformation via Explicit Finite Element method. Assadi in [3] propose a method for spotting shear instabilities using the Explicit Finite Element method. The methodology implemented consists in performing multiple FEM runs in order to spot the velocity where the shear instability is triggered.

4. *Semi-emphirical model.* In [4], Assadi proposes semi-emphirical model for calculating the critical deposition velocity. The model, uses the Johnson Cook equation for thermal softening, a ballistic expression for crater

ground pressure in hydrodynamic penetration and the energy balance between thermal dissipation and kinetic energy correlated with empirical weighting factors.

For all the approaches used for calculating the critical deposition efficiency, it is understood that it is a function of the material mechanic properties, diameter of the particle, temperature of the particle and impacting velocity. The critical velocity is not a function of the melting temperature of the material [5]. In [4] the concept of “Parameter window of deposition” is introduced. The concept of “Window of Deposition” is defined, as the range of velocities at which deposition can occurs; there is a minimal value in the window of deposition is the critical deposition velocity and the maximal value in the diagram is known as the “erosion velocity” where the material erodes and affects the overall deposition efficiency.

2. Computational Fluid Dynamics model

In order to study the gas dynamic parameters of the air being expanded through the divergent part of the nozzle, the Computational Fluid Dynamics (CFD) method is used. Solidworks Flow Simulation© is used in order to simulate the fluid dynamic properties of the expanded flow on which the thermal energy is transformed into kinetic energy by the variation of the area in the SK-20 nozzle. The SK-20 nozzle is drawn and several simulations runs are performed for 424 C, 526 C and 632 C stagnation temperatures T_0 with a stagnation pressure P_0 of 0.8 MPa in all the cases. A substrate is located at 10 mm from the nozzle exit in order to simulate the gas shock while impacting a surface.

The simulation is performed for a 2-Dimensional plane of the nozzle that is considered symmetrical for the complete geometry. The computational domain is restricted for *X* between -8mm and 142mm and for *Y* between -7.5 and 7.5mm. The fluid cells for the model are 119422 cells while the cells for the solid are 31108. The calculations are performed with a reference ambient pressure of 0.1MPa and a reference ambient temperature of 20.05 C. A turbulence intensity of 2% is considered with a length of 1e-4m. The boundary layer is considered turbulent for this case. Fig. 1 shows the SK-20 nozzle geometry with an initial mesh.

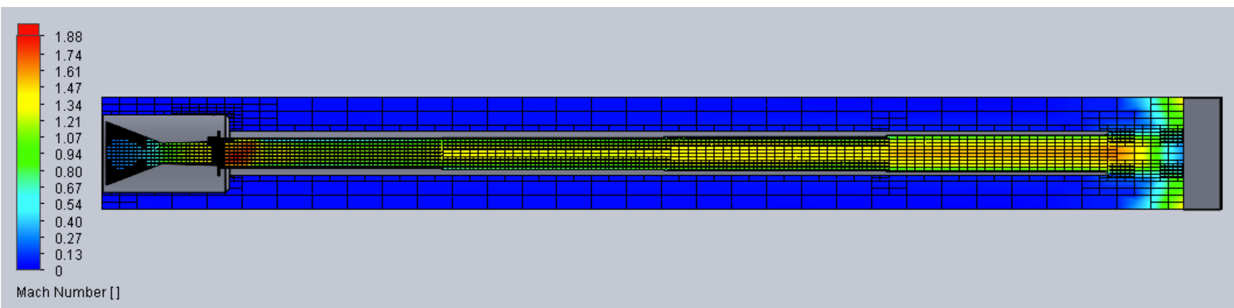

Figure 1 – SK-20 Nozzle profile with a contour plot of the developed Mach number at T_0=632 C and P_0=0.8MPa with an initial mesh

In order to study the interaction of the gas with the injected powder materials a "particle study" for each for the particles mentioned at the begging of this chapter is performed. Solidworks Flow Simulation© particle study unlike to the isentropic method, calculates the particles interaction with the gas taking into account a variable drag coefficient as a function of the Reynolds and the Mach number of the particle, and with heat capacity as a function of temperature. As well, the "particle study" takes into account the stochastic nature of turbulence and how it affects the particles trajectory through the SK-20 Nozzle.

3. Critical particle velocity determination

In this section the critical velocities for Nickel, Aluminum, Copper and Zinc powders is calculated for a particle size of 25μm; the critical velocities are calculated for the spraying parameters of the DYMET 405 Low Pressure Cold Spraying equipment at stagnation pressures of T_0=424 C, T_0=526 C and T_0=632 C.

In order to calculate the critical velocity of 25μm the equation presented by Assadi in [4], is used Eq. 1,

$$V_{crit} = \sqrt{\frac{F_1 \cdot 4 \cdot \sigma_{TS} \cdot \left(1 - \frac{T_i - T_R}{T_m - T_R}\right)}{\rho_p} + F_2 \cdot c_p \cdot \left(T_m - T_i\right)}, \quad (1)$$

Where V_{crit} is the particle critical velocity, σ_{TS} is the tensile strength of the particle material, T_i is the impact temperature of the particles, T_R is the reference temperature (293 K), T_m is the melting temperature of the particle, ρ_p is the particle density, c_p is the heat capacity of the particle, and F_1 with F_2 are empirical coefficients with the values of 4.8 and 1.2 respectively for the critical velocity and F_1=4.8 and F_2=1.2 for erosion velocity obtained by correlating experimental results.

In the critical velocity equation presented by Assadi the tensile strength of the material is combined with the Johnson-Cook equation for thermal softening in order to represent a temperature related material strength. The material strength of the material is compared to the pressure in hydrodynamics ballistic penetration. As well the kinetic energy dissipation into heat is considered into the equation and both of the factors are correlated by a 0.5 factor plus empirical coefficients F1 and F2. The impact velocity and impact temperature of the particles at different stagnation temperature values is calculated using the CFD methodology and presented in Table 1 Fig. 2 shows the critical velocities from the selected powder materials.

Table 1 – Impact velocity and impact temperature of selected powder materials with 25μm diameter calculated with CFD methodology for T_0=424 C, T_0=526 C and T_0=632 C of the DYMET 405 Low Pressure Cold Spraying equipment.

	T_0=424 C		T_0=526 C		T_0=632 C	
Material	V_{pImp} (m/s)	T_{pImp} (K)	V_{pImp} (m/s)	T_{pImp} (K)	V_{pImp} (m/s)	T_{pImp} (K)
Nickel	309.71	406.77	331.15	436.12	350.77	464.56
Aluminum	418.24	407.45	452.54	437.77	481.68	467.63
Copper	309.22	420.16	330.61	454.36	350.19	488.29
Zinc	329.49	430.41	352.84	467.16	374.15	503.56

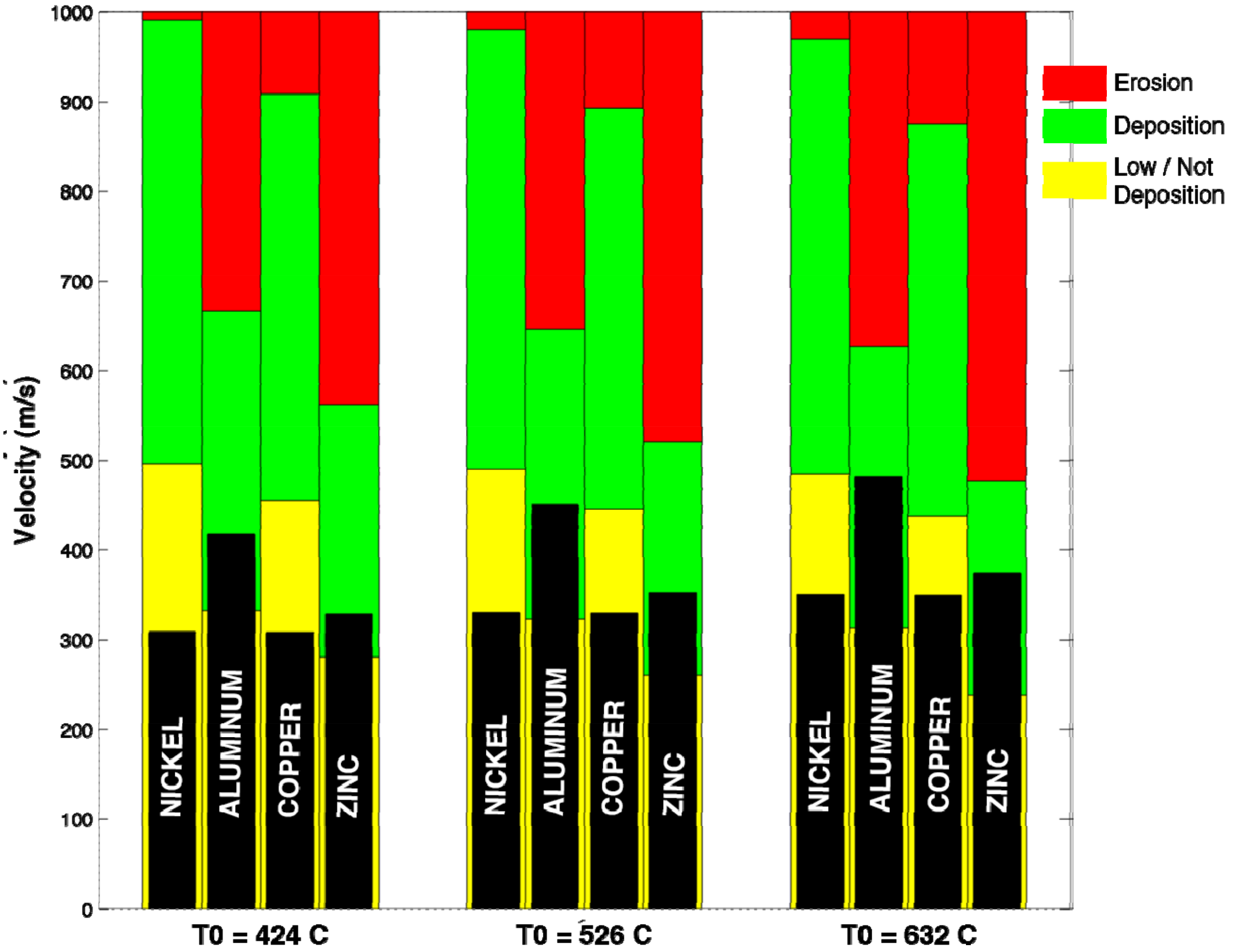

Figure 2 - Schematic Erosion and Critical velocities (on red and green) for selected 25μm powder materials sprayed at different stagnation temperatures with the DYMET 405 Low Pressure Cold Spraying equipement; black bars represent the impact velocities for each powder material

Conclusion

It was shown in this study the calculation of critical and erosion velocities for low pressure cold sprayed nickel, aluminum, cooper and zinc powders with a size distribution of 25um. In order to determine the particles impact velocity and temperature, the computational fluid dynamics methodology was applied with a particule study on the SK-20 nozzle during the operation of the Dymet 405 Low Pressure Cold Spraying system at several stagnation temperatures. Using the data for the particles impact velocity and temperature obtained from computational fluid dynamics methodology the critical and erosion velocity of the powder materials was determined by the Assadi's critical velocity equation. In this study it was found that aluminum and zinc particles with a 25um size distribution reach the critical velocity on every studied stagnation temperature while being sprayed with the Dymet 405 Low Pressure Cold Spraying system; cooper and nickel powders did not reach the critical velocity at any studied stagnation. Since the powder materials used for low pressure cold spraying are usually metal matrix composite blends, it can be deduced that the reinforcement part of the matrix - alumina and zinc - help the main metal part to increase deposition [9, 11]. It should be noted that this study is limited to 25um and in realty the critical velocity of powders is also a function of the particle diameter; for this reason, further research on particles critical velocity calculation is recommended.

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