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Development of a deposition strategy in Cold Spray for Additive Manufacturing to minimize residual stresses

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Abstract

Cold Spray (CS) is a rapidly developing metal deposition technology, which allows for the formation of coating layers in a melt-free manner and is starting to replace existing technologies at industrial level. New developments in the field of CS as well as optimization of spraying strategy permit to elaborate freeform 3D objects with reasonable precision. Residual stress is among the most important factors affecting coating integrity in fact they can lead to peeling and/or delamination of coatings. In this study two different types of simulation were performed: at the microscale, using ANSYS-AUTODYN, a high impact simulation in order to study the mechanism of formation of residual stress in the cold-sprayed deposited particle; and at the macroscale a static structural simulation based on Tsui and Clyne's progressive deposition model in order to investigate a possible interaction between different layers and developing a deposition strategy. For the first time, in this work, a parametric study of the single impact particle to study the residual stress was proposed finding that impact velocity; incident angle of impact and density and the yield stress for the materials involved in the deposition have a strong influence in the residual stress formation. Furthermore, at a macroscopic scale, a deposition strategy that minimises residual stress was identified. In fact, it was found that the deposition of successive layers with a perpendicular relative orientation leads to a final product with lower residual stress.

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Keywords: Cold Spray; residual stresses; Deposition; Particle impact; FEA.

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1. Introduction

Cold Spray (CS) is a novel metal deposition technology, which allows for the formation of coating layers in a melt-free manner and is starting to replace existing technologies at industrial level. This CS process is an exciting new spray technology that has the potential to overcome limitations of more traditional thermal spray processes for some important commercial applications. It is possible to rapidly deposit thin or very thick layers of a wide range of metals, and even some composite materials, without melting or vaporization, at or near room temperature, in an ambient air environment [1].

In CS inert gases (such as Nitrogen or Helium) are fed at high pressure in the inlet of a supersonic nozzle. The gas expands in the nozzle, and can reach at the exit velocities well above 3600Km/h. Such high speed jet is used to accelerate small metal particles, which are made to strike upon a substrate material. If a threshold energy level is reached at impact, the particles will bond to the substrates and form a coating. New developments in the field of CS as well as optimization of spraying strategy permit to elaborate freeform 3D objects with reasonable precision. The great advantage of CS is its ability to fabricate multi-material, intermetallic, and functionally graded components. However, further work is needed to develop the process and to address challenging

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technological issue such as stable powder feeding and optimization of spraying strategy [2].

Residual stress is among the most important factors affecting coating integrity; it can lead to peeling and/or delamination of coatings. Thus, understanding of the bonding mechanism together with the stress formation is critical for improving the overall integrity or performance of the deposition. Up to now, there is a limited amount of data detailing the residual stresses in cold-sprayed materials whether inside a single-deformed particle or the whole coating, though there have been several investigations on residual stress of thermal sprayed coatings. For CS, Tsui and Clyne developed a model [3] capable of predicting the residual stresses profile through the thickness of the deposition. Numerical simulations of a single particle splat [4,5], multi-particle impact [6,7] and single pass [4] are present in literature.

Deposition strategies that minimise residual stresses have already been developed and present in literature for thermal spray, giving more emphasis to the effect of the temperature distribution on the substrate, that is irrelevant in CS application; or simply optimizing the spray angle, the relative speed and distance between torch and component and maintaining them constants during the manufacturing process [8-10]. From the literature review emerged that although CS is rapidly imposing itself as a promising technique for additive manufacturing application, few researches tried to develop a deposition strategy that has as objective the minimisation of residual stress.

Moreover, only the influence of variation of impact velocity, initial temperature and the utilisation of materials such as aluminium and copper has been analysed on the mechanism of formation of residual stress in CS. For this reason, in this study, the implementation of different numerical approaches for the single particle impact was conducted in ANSYS-AUTODYN and then, the analysis of the effects of oblique impact, variation of friction coefficient and the utilisation of titanium together with aluminium and copper, was performed for a better understanding of the mechanism of formation of residual stress.

2. Model Description

2.1. Single Particle Impact

The residual stress derived by the single particle impact was simulated in this study, using the commercial software ANSYS-AUTODYN. The simulations of the parametric study were performed using the Lagrangian model.

Table 1 presents the outline of the parametric study, focusing on the four parameters: materials combination, orientation of impact, impact velocity and frictional coefficient. The values of size, velocity and friction coefficient are tipical values present in the litterature for this type of analysis.

In order to model the complex response of materials to dynamic loading in our particular study, two components are needed: an equation of state that describes the hydrodynamic response of a material and material strength laws that describe the nonlinear elastic-plastic behaviour.

SHOCK EQUATION OF STATE (EOS) LINEAR:

This model uses a Mie-Gruneisen form of the equation of state based on the shock Hugoniot. The pressure p is determined as a function of density ρ and the specific energy E by:

$$p = p_H + \Gamma\rho(E - E_H) \tag{1}$$

Where it is assumed that:

$$\Gamma = \Gamma_0 \frac{\rho_0}{\rho} \tag{2}$$

$$p_H = \frac{\rho_0 c_1^2 \mu(1+\mu)}{[1-(s_1-1)\mu]^2} \tag{3}$$

$$E_H = \frac{1}{1}\frac{p_H}{\rho_0}\left(\frac{\mu}{1+\mu}\right) \tag{4}$$

Where p_H and p_H are the Hugoniot pressure and specific energy; Γ the Gruneisen ratio; Γ_0 a material constant; ρ_0 the reference density; $\mu = -1 + \rho/\rho_0$ the compression and c_1 and s_1 define the linear relationship between the linear shock velocity U_s and the particle velocity U_p as follow:

$$U_s = c_1 + s_1 U_p \tag{5}$$

JOHNSON-COOK STRENGTH:

This is the most suitable model to represent the strength behaviour of materials, typically metals, subjected to large strains, high strain rates and high temperatures, as it happens in our simulation. With this model, the yield stress varies depending on strain, strain rate and temperature.

The model defines the yield stress Y as:

$$Y = [A + B\varepsilon^n][1 + C ln\dot{\varepsilon}^*][1 - T^{*m}] \tag{6}$$

Where ε is the equivalent plastic strain; ε ̇^*=ε ̇/ε ̇_0 is the dimensionless plastic strain rate for ε ̇_0=1.0s^(-1); T^*=(T-T_0)/(T_m-T_0) is the corresponding temperature; n is the work hardening exponent; A, B, C, and m are material constants; T is the temperature in Kelvin; Tm is the melting temperature of the material; and T0 is a reference temperature.

We assumed a perfectly spherical shape for the particle of Al, Cu and Ti as indicated by scanning electron microscope (SEM) observations present in the literature [12]. In the simulations, the height and radius of the substrate has been chosen to be ten times larger than the particle radius in order to reduce the number of elements of the mesh and therefore the calculation time. Moreover, it has been made sure that the