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Study of Multi-Splat Layer Formation in the Cold Spray Process

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Abstract: In this study, the deposition of a series of splats onto a solid substrate by the cold spray process has been investigated through modeling. Traditional approaches to modeling particle deformations and splats are based on the distribution of kinetic energy, elasticity and fluidity of particles impacting the surface, and are computationally impractical to simulate a bulk sample with statistical distributions of particle shape, size and various experimental conditions. In this work we demonstrate that by using empirical and phenomenological statistical relationships among particle size, speed, material strength and impact elongation, it is feasible to realistically simulate virtual experiments under various experimental conditions.

In the cold spray process, solid state powders, with particle sizes ranging from several to tens of micrometers in diameter, are accelerated to supersonic velocities. Upon impacting the substrate, these particles undergo plastic deformation and subsequently adhere to the surface. The collision dynamics of these micrometer sized particles impacting onto a solid substrate leading to the formation of a coating several hundreds of micrometers thick are studied by means of two-dimensional computer simulations. The experimental observations and the numerical results are in reasonable agreement.

Keywords: *cold spray, particle impact, modeling, splat, coating.*

1. INTRODUCTION

Cold spray, or cold gas-dynamic spraying, is a surface coating technology in which small, solid state particles are accelerated to high velocities (normally in the range 300–1200 m/s) in a supersonic gas jet, which are then deposited onto a substrate material. A schematic diagram of a typical cold spray system is illustrated in **Figure 1**. Upon impacting the substrate, the particles will deform and adhere to the surface, forming what are referred to in this work as splats. Particle adhesion is only possible if a critical velocity for the particle is reached.

The deposition of particles takes place through the intensive plastic deformation upon impact. The mechanism for metallic bonding achieved through cold spray has been compared with explosive welding, in which (at a certain velocity upon impact) thin films on the accelerating particles' surfaces are ruptured, generating a direct interface (Alkhimov et al. 1994, Gilmore et al. 1999, McCune et al. 1995).

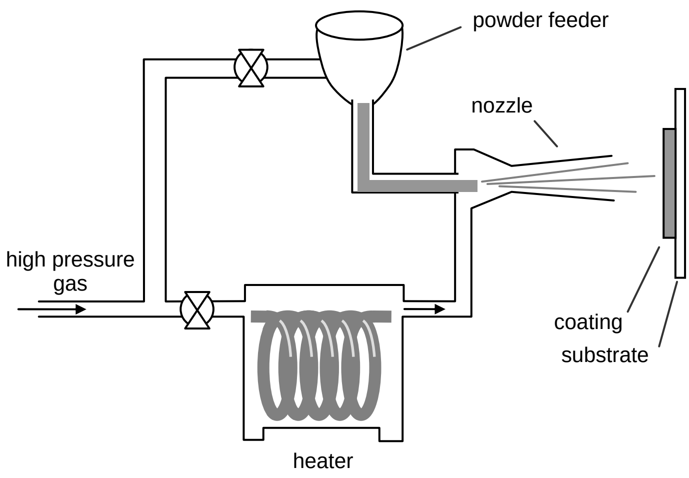

Figure 1. Schematic diagram of a cold spray deposition system.

The bonding of the particles to the substrate relies on sufficient energy to cause significant plastic deformation of the particle and/or the substrate. When subjected to the high impact stresses and strains of such a collision, the interaction of the particle and substrate surfaces may result in the disruption of oxide films/layers present on their surfaces, promoting contact of chemically clean surfaces and high friction, generating very high localized heating that promotes bonding similar to friction or explosive welding.

The efficiency and quality of the bonding is influenced by geometrical, mechanical and chemical factors. The particle impact behavior also strongly depends on the hardness ratio of the accelerated particle and the substrate on which it impacts (Bae et al. 2008). For example, a soft/soft (soft particle impacting on a soft substrate) interaction will generally result in a partial penetration of the particle into the substrate, as will a hard/hard interaction. On the other hand, a hard/soft interaction tends to result in the particle becoming impregnated deep within the substrate surface, whilst a soft/hard interaction results in virtually no penetration of the particle into the substrate, with the particle becoming increasingly flattened as its velocity is increased.

Copper has often been employed as standard material to describe high-strain-rate deformation behaviors, such as the adiabatic shear instability, because it is feasible to simulate its behavior, and highly reliable high-strain-rate material data are available. In this paper we present several simulations of multiple copper particles deposited onto a solid substrate by the cold spray process. The devised program is capable of simulating thousands of particles to produce layers whose thicknesses lie in the millimeter range. Such a large number of particles may be modeled as we have utilized empirical and phenomenological statistical relationships among particle size, speed, material strength and impact elongation to realistically simulate the layer formation. This approach is unlike traditional approaches for modeling splats, which are typically carried out by finite element methods and are based on the distribution of kinetic energy, elasticity and fluidity of particles impacting the surface. Although such techniques describe to some degree the deformation and solidification processes occurring during cold spray deposition, it can be computationally impractical to simulate a bulk sample with statistical distributions of particle shape, size and various experimental conditions.

2. MODEL

Simulations were carried out in a two dimensional matrix, labeled the 'event matrix', of size 500×1000, with each element (pixel) in the matrix corresponding to an area of 1×1 μm^2. Particles were elongated prior to entering the event matrix, and this elongation was determined by equations obtained from prior examination of various micrographs of surfaces and cross sections of copper cold spray coatings.

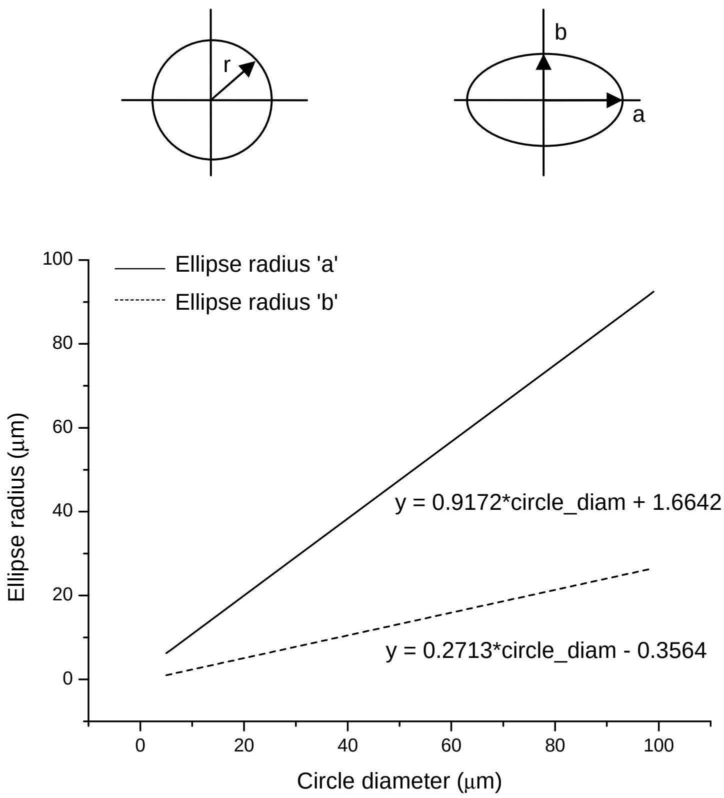

Figure 2. Particle elongation

In the cold spray process, the velocity of the accelerated particles is largely dependent on its dimensions, with smaller particles having a propensity for being accelerated to greater velocities in the gas stream than larger ones. These smaller particles exhibit the greatest deformation and elongation.

The cold spray powders in this system were assumed to contain particles that are approximately spherical. As the model employed here is a two dimensional one, such particles are thus represented as circular.

The approach taken for elongation involved transforming a circle to an ellipse of equivalent area. From the data available, the smallest particle diameter we have considered was 5 μm (radius 2.5 μm). Hence this size particle will travel with the greatest velocity and consequently will be elongated the most. Similarly, the largest particle considered was of size 99 μm (radius 49.5 μm) and will be elongated the least. Based on this data, the equations governing the elongation were obtained and may be seen in **Figure 2**.

A Gaussian random number generator based on the Box-Muller transform (Box and Muller, 1958) was utilized for generating the values of the circle diameter. As the particle's size is known, so too is its velocity, and hence its momentum may be calculated.

Once elongated, the pixel representation of the randomly generated particle was transferred to the event matrix, to a random position as determined from a uniform distribution whose range lies between 0 and the width of the event matrix. From here, the perimeter of the particle is continually scanned for a collision with the substrate or any underlying material that was previously deposited. If no collision is detected, the particle is dropped down one level in the matrix and its perimeter is subsequently rescanned.

If a collision is detected, then all the pixels which are in contact with the underlying material are redistributed to free sites on the particle's perimeter, i.e. those which are not in contact with anything. Once all these pixels have been redistributed, the particle's momentum is adjusted by an amount proportional to the number of pixels involved in the collision. This corresponds to a decrease in the particle's post collision velocity. The particle is then dropped down one level in the event matrix, where its perimeter is once again scanned. This process continues until the particle's momentum is reduced to a certain threshold value, below which the particle ceases to move and its position is secured. Following this, a new particle is transferred to the event matrix and the process repeats itself.

In a previous experimental study of cold spray deposited copper (Zahiri et al. 2006), the effect of particle size and particle size distribution on porosity formation were examined by utilizing two types of powders. The first (powder I) had an average particle size of 18 μm whilst the second (powder II) had an average particle size of 28 μm. Both powders were examined for a range of spray temperatures and pressures during their deposition. In this work, we compare simulation results with those determined by (Zahiri et al. 2006) in terms of porosity. The simulations yield a two dimensional output, though porosity is based on a volumetric percentage. Hence we have taken the output as being representative of a slice of a three dimensional coating and calculated porosity as the percentage of unfilled pixels.

3. SIMULATIONS

The simulations were carried out on a Dell XPS M1210 laptop computer running Windows XP Professional, with an Intel Core 2 CPU T7200, 2.00 GHz and having 2GB of RAM. The simulation program was written in MS Visual C++ 2005. Data and imaging processing were carried out using MATLAB Version 7.0 (R14).

The simulated output of the program illustrating the time evolution cross section of a copper coating being formed on a solid substrate is shown in **Figure 3**. The particle size distribution employed was Gaussian, with a mean particle size of 33 μm and a standard deviation of 10. It is clear that as the coating's thickness increases, the presence of pores and voids becomes apparent. These pores can range from the more frequently occurring sizes of ~1 μm^2 to the less commonly occurring pore sizes > 130 μm^2.

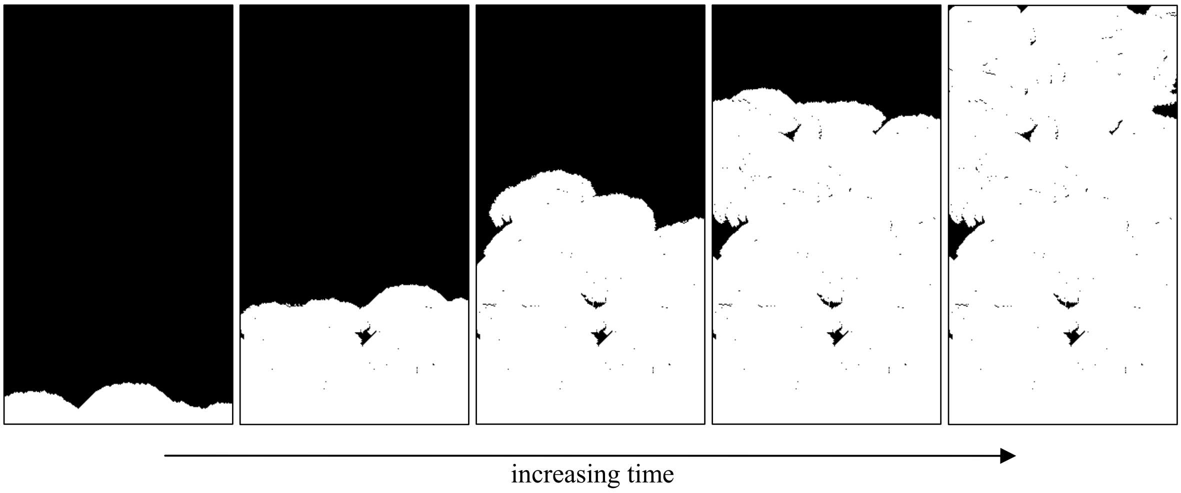

Figure 3. A time slice of a segment of the simulation output depicting the cold spray deposition process (each image has dimensions 470 × 255 μm). The dark areas correspond to voids whilst the white areas correspond to those containing copper.

The void present in the above images most likely appear as a result of bridging of the particles. Ideally, larger particles entering the gas stream tend not to achieve the gas stream velocity, and consequently experience only a limited plastic deformation, or flattening, during the deposition process. On the other hand, the particles may in fact achieve the required velocity for deposition, yet microstructural porosities develop due to both inter-particle gaps and particle bridging, and hence the larger pore sizes can observed, as in the model output in **Figure 3**.

Figure 4 shows sections of simulations of two different copper coatings, where the parameters and statistical distributions were adjusted to produce a coating in keeping with those found in (Zahiri et al. 2006) for powders I and II. From literature, the volume fraction of porosity for the coating formed from powders I and II were experimentally around 0.5 and 1.5%, respectively. The particle size distribution utilized for simulating powder I was Gaussian, with a mean of 18 μm and standard deviation of 2, with the simulation resulting in coating having a porosity of 0.413%, a value that is agreeable with experiment.

The simulation for powder II was carried out with a Gaussian particle distribution with mean particle size of 28 μm and standard deviation of 8. A distinct difference in the cross sections of two coatings is evident, as observed from the figure. There is a significant increase in pores and voids, both as a result of the much larger particles present in the system experiencing limited plastic deformation and due to an increase in particle bridging. The resulting porosity of this coating had a value of 1.617%.

Simulations carried out also demonstrated that porosity and hence the underlying microstructure may be tailored by selecting the appropriate particle size distribution of the cold spray powder. For example, to obtain a material with few pores, a particle size distribution with smaller standard deviation and mean size should be utilized (such as for powder I). However, for a uniform distribution of smaller pores and a limited number of voids, then a particle size distribution containing a small standard deviation and larger mean size should be employed. Hence the simulations show that control over the porosity formation in cold spray coating may, to a certain degree, be realized through changing the particle distribution, where coatings with a comparable porosity to those obtained experimentally can be produced.

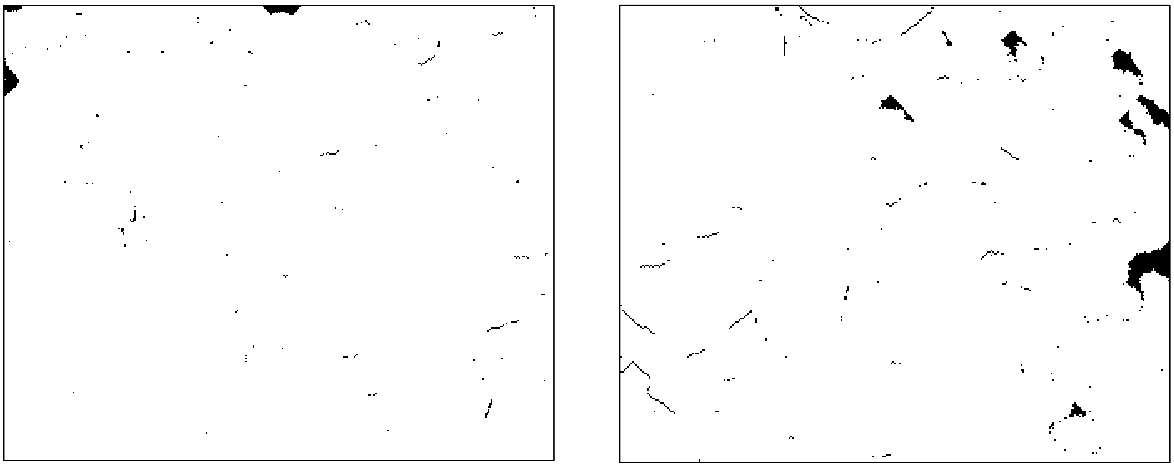

Figure 4. Simulation output of powder I (left) and powder II (right)

4. SUMMARY AND FUTURE WORK

The major processing conditions affecting porosity formation in a cold spray coating are the particle velocity, particle temperature, and particle size distribution. As was seen in this work, for smaller particles whose size distribution had a relatively smaller standard deviation, coatings with a reduced number of pores and bridges are produced. We have shown that the model can program can reproduce quite well the cold spray deposition of copper, with the calculated values of porosity corresponding to those obtained from experiment.

This work is in its preliminary state and plans are underway to simulate the effect of varying various other parameters in the cold spray deposition process. One particular aspect of interest is the nozzle standoff, which is the distance between the cold spray system’s nozzle and the substrate to be coated. The standoff distance strongly influences the particle velocity and thus the deposition efficiency. We are also currently developing the model for simulating different types of interactions (soft/soft, hard/hard, soft/hard, hard/soft) in order to study the deposition of different material combinations. Additionally, the model in its current state is two dimensional, and steps are underway to make it a three dimensional one.

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