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Publisher’s version / Version de l'éditeur:

59th Annual Conference of Metallurgists: Emerging Technologies in Materials and Metallurgical Industries, 2020-08

IS COLD SPRAY ADDITIVE MANUFACTURING?

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Key words: Cold spray, additive manufacturing.

Abstract

Cold spray is fundamentally a powder consolidation method in which the powders are accelerated to supersonic velocities such that, on impact, the particles bond. It belongs to the thermal spray family of coatings, but because of the relatively rapid build up rate, 3-D thicknesses 'coatings' can be quickly created, imparting additive manufacturing characteristics to this technique. This paper will overview the process, describing the basic mechanisms of consolidation and describes the technologies associated with future positioning of this technology in additive manufacturing.

Introduction to cold spray

Cold gas dynamic spray is essentially a powder consolidation technology that can be considered to be a high kinetic energy coating process as well as a free-form fabrication process [1-3]. The cold spray process (Figure 1) makes use of a high pressure compressed gas, with velocities that vary from 500 to 1500 m/s, to accelerate solid particles (usually metallic powders with sizes ranging from 1 to 50 µm) onto a substrate under atmospheric conditions [1-3]. On impact the particles plastically deform and adhere onto the substrate and each other [1-4].

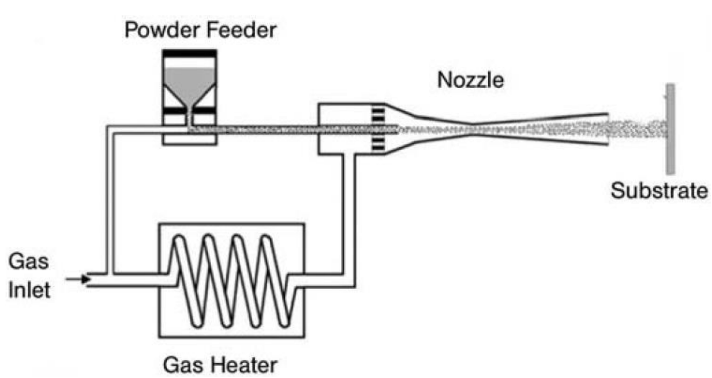

Figure 1: Schematic of the cold gas dynamic spray process [5].

As can be seen in Fig. 1, a compressed gas (usually nitrogen or helium) at pressures between 1.0 and 5.0 MPa flows through the system in two different paths. In one path, the gas flows through a powder feeder carrying the powder into the gun. Most cold spray nozzles are converging/diverging De Laval type nozzles, which allows the gas and the particles to reach supersonic velocities 1-3]. In the other path, the gas flows through an electric gas heater, which preheats the gas to temperatures ranging from 100ºC to 1100ºC [1-3], further increasing the gas velocity and, consequently, the particle velocity. At the nozzle exit, the high temperature gas and the particles reach supersonic velocities, impact on the substrate surface, consolidate on the substrate and layers of the depositing material are deposited. Note that even though the inlet gas is preheated to high temperatures, the particles remain in the solid state because the contact time between the high temperature gas and the particles is relatively short. In addition, the gas sharply decreases in temperature as it expands through the divergent section of the gun nozzle [1-3], such that the temperature at which the powders impact is much lower than that of the heated gas. Thus, this process reduces the detrimental effects of high temperatures, such as oxidation, phase transformation and grain growth [3].

Bonding/Adhesion Mechanisms and Critical Velocity

As mentioned above, plastic deformation must occur for bonding between particles and/or substrate to take place. The exact mechanisms of bonding are still in question, but there are two broad categories: (i) physical interlocking and (ii) metallurgical bonding.

The physical interlocking approach has its basis in explosive welding [2] where interlocking is engendered by the formation of waviness at the interface between two surfaces that have been explosively impacted together. Alternatively, there may be some microscale interlocking of fine scale asperities, however this is not easily observed.

Metallurgical bonding is essentially atomic level 'coulombic' bonding in which plastic deformation leads to two stages of bonding: (i) breaking of the oxide film to reveal pristine metal surfaces and (ii) intimate contact of the pristine surfaces to effect coulombic bonding. However, these two events are apparently not sufficient to achieve bonding; in fact a critical *velocity* must be exceeded before bonding takes place. As can be seen in the effect of particle velocity on deposition efficiency (DE = % age of powder sprayed that deposits), Fig 2, below the critical velocity, there is a small amount of erosion, but as soon as the critical velocity is exceeded, the DE increases rapidly. It is unclear as to why a critical velocity is necessary, but it is associated with adiabatic shearing, i.e. a very high strain rate localised at the particle interface, characterized by material jetting (Fig. 3).

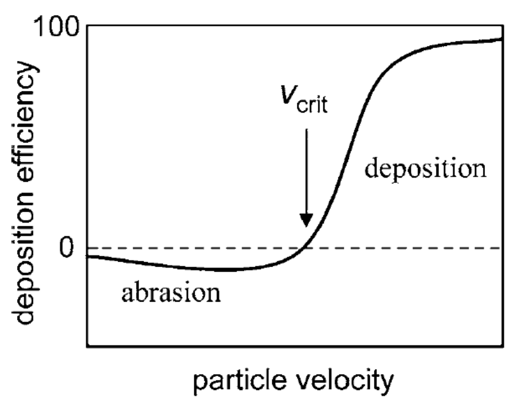

Figure 2: Schematic of the dependence of deposition efficiency on particle impact velocity [6].

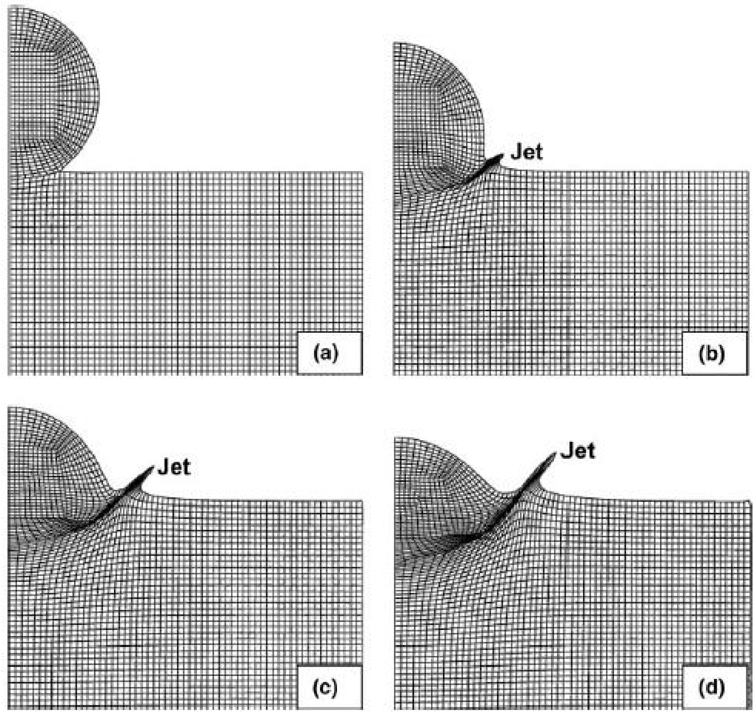

Figure 3: Temporal evolution of an impacting copper particle onto a flat copper substrate during cold spray from finite element analysis (a) 4.4 ns, (b) 13.2 ns, (c) 22.0 ns, and (d) 30.8 ns [7].

Mechanistically, it is possible that such a large amount of plastic deformation is required to break and reveal a significant area of pristine metal; a high level of localised heating that may be associated with adiabatic shear may also play a role in bonding.

Effect of process parameters on powder consolidation characteristics

As mentioned above, deposition efficiency is one of the main characteristics of cold spray consolidation; the other important metrics are porosity (or 'density'), mechanical properties and adhesion strength between coating and substrate.

The main process parameters are gas temperature and pressure, which, for a given nozzle geometry, control the velocity of the particles. As was seen in Fig. 2, particle velocity is regarded as being the first order variable that controls powder consolidation characteristics, although the fundamental parameter is actually impact force. In any case, increasing temperature and pressure increase particle velocity, and this not only increases the deposition efficiency, but also decreases the porosity. The reason why increasing velocity increases the DE is possibly connected with increases in heat generated locally at the impacting interfaces, although it is not clear why the DE increases so rapidly above the critical temperature. Porosity decreases simply because the amount of plastic deformation increases enabling the particle shapes to change to fill in the porosity defined by particle packing density [8]. Although gas pressure and temperature combine to control particle velocity, there are additional effects of increasing gas temperature in that the particles also increase in temperature. This should decrease the yield strength of the particles and substrate, which will tend to increase the DE and decrease the porosity [9]. However, the effect on yield strength is still very much a second order effect compared to particle velocity, even though the effect of temperature on yield strength is exponential.

Other process parameters are the powder feed rate, the stand off distance (distance from the gun exit to the substrate) and the scan rate of the gun over the substrate. These, at best, impart second order effects on coating metrics. Of these, low powder feed rate and scan rates could increase the substrate temperature, leading to more plastic deformation, which, in turn, would generally increase DE and decrease porosity [10].

In theory, there is a specific stand off distance that will maximize the velocity of the powder at impact, but, as noted above, it is not a significant effect compared to gas temperature and pressure.

The high pressure compressed gas used to propel micron-sized particles onto a substrate in cold spray is usually composed of nitrogen or helium [1-4]. It has been shown that cold spraying with helium gas results in a much higher particle impact velocity compared to nitrogen gas with the same or slightly lower inlet gas temperature [8,11]. This is because the gas velocity is an inverse function of gas molecular weight and, of course, the molecular weight of He is far lower than that of N. Because of cost and sustainability issues, nitrogen is still very much favoured over He.

Effect of powder characteristics on powder consolidation metrics

Schmidt et al. [12] have developed a semi-empirical equation for predicting critical velocity (v_{cr}):

$$v_{cr} = \left\{\left[4F_1\sigma_{TS}\left(1 - \frac{T_p - T_{Ref}}{T_m - T_{Ref}}\right)\right] + T_2 c_p\left(T_m - T_p\right)\right\}^{\frac{1}{2}}$$

Where σ_{TS} is the ultimate tensile strength, T_p is particle temperature at impact, T_{Ref} is the temperature at which the ultimate tensile strength was determined (taken in this case as 293 K), T_m is the melting point, c_p is specific heat and F_1 and F_2 are material dependent calibration factors.

However, experimental evidence [13] suggested that V_{crit} is dependent on particle size, with V_{crit} decreases with increasing size until a plateau is reached. Assuming a particle bonding mechanism based on breaking oxide films to create reactive surfaces and the adiabatic shear mechanism, a decreasing particle size leads to increasing oxide film surface area per unit volume and increasing rates of thermal diffusivity, the latter making it difficult to reach the temperatures required for the adiabatic shear mechanism to be activated. Modelling these two aspects accurately is difficult, so an empirical approach has been developed by Schmidt, et al. [14] as per equation below:

$$c_{cr} = v_{cr}^{ref}\left(d_p/d_p^{ref}\right)^{-0.18}\sqrt{1 - T_p/T_m}$$

Where d_p is particle size and V_{cr}^{ref} is the critical velocity of a reference particle size d_p^{ref}.

In general, for a given nozzle geometry, gas pressure and temperature, fluid flow analysis reveals that increasing the particle size decreases the velocity of the particle. However, in the presence of a substrate, there is the so-called 'bow shock' immediately in front of the substrate, which tends to decelerate all particles. The level of deceleration depends on the particle size, with very small particles being strongly affected by the bow shock such that, below the optimum size, increasing particle size leads to increasing velocity until the optimum size, which corresponds to the maximum velocity, is reached. Combining the effect of particle size on critical velocity and particle velocity, a particle size range is defined not only where the particle velocity is greater than the critical velocity, but a particle size range that maximises this difference between the velocity and the critical velocity (Fig. 4).

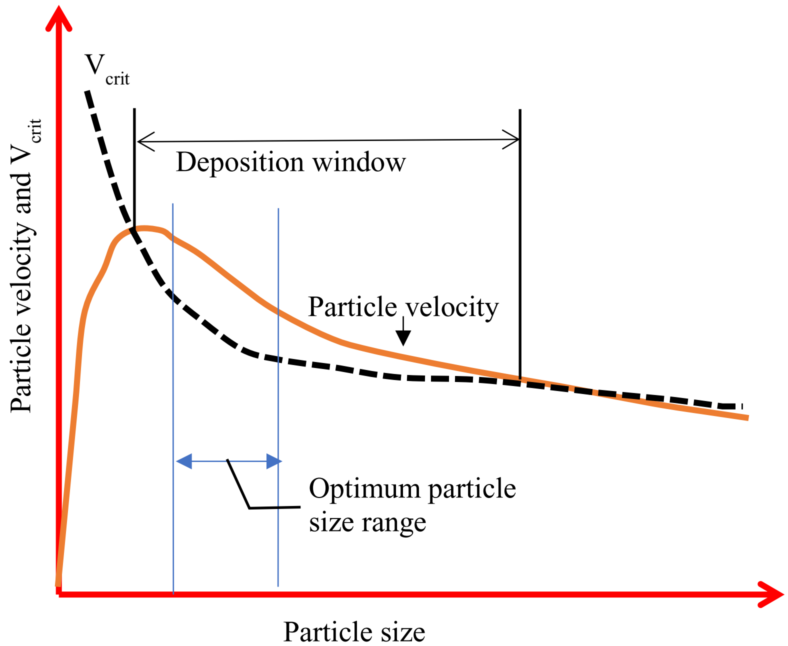

Figure 4 Schematic diagram showing the effect of particle size on critical velocity and particle velocity, which defines the optimum particle size range for cold sprayability [15]

Cold Spray as an Additive Manufacturing Technology

The fact that cold spray is a method to consolidate metal powders automatically makes it under consideration as an additive manufacturing method. In fact, one of the main initial attractions of cold spray was to radically improve the buy-to-fly ratio of aerospace components. The commonly cited example is the creation of 'bosses' on components, which was probably conceived of because cold spray began 'life' as a coating technology. However, one of the main differences between cold spray and other thermal spray methods, as mentioned above, is the rapid deposition rate, which effectively transitioned cold spray from 2-D coatings into 3-D coatings, and from there, to additive manufacturing. Returning to the manufacturing of a part containing a boss, if a boss is created by conventionally (i.e. subtractively) machining an 'oversized' blank, it is clear that this leads to considerable material wastage, compared to 'adding' onto a blank of the correct dimensions. In aerospace, the metals tend to be relatively exotic, thus making the buy-to-fly ratio a very important economic factor and a positive aspect of cold spray.

One of the main challenges of using cold spray as an additive *machining* technology is the adhesion between the cold sprayed feature and the substrate. The main problem is residual stress caused by deformation at the substrate; increasing deposition thickness increases the tendency for delamination. Obviously, relieving this residual stress is one concept to prevent delamination; another approach is to improve the adhesion between the feature and the substrate. The concept of hybrid machining is one way to address these issues.

The literature clearly indicates that, for current hard-to-spray materials, the cold spray process in isolation is insufficient to obtain performance equivalent to conventional cast or wrought products. A hybrid manufacturing cell, which pairs laser technology with cold spray, will have considerable potential for improving the properties of the as-consolidated material, although defining the process-property relationships will be very challenging. This type of hybrid processing has, thus far, been under-explored because there are few research centres possessing the capability and expertise.

Past investigations in the McGill-NRC facility with a high frequency and high power ablation laser showed high potential to increase the bond strength of cold spray deposition onto a substrate surface. The effect was demonstrated using aluminum [16] and titanium and nickel base alloys [17], which showed clean interfaces (without cracks, embedded grit, etc.) compared to those obtained after processing by grit blasting. The clean interfaces will likely be critical for effective material response to post-spray processing (e.g., heat treatment) and associated improvement in material consolidation by diffusion-related mechanisms (e.g., 'sintering' across the interfaces). The ablation laser, which could be installed together with the cold spray gun on the same robot, would provide surface pre-treatment/cleaning prior to spray; this can be for the substrate and/or robot machined surfaces. Process automation ensures cold spray deposition can occur on a freshly cleaned surface, hence maximising particle bonding and deposit adhesion. This non-contact, non-abrasive process also includes the important benefit of eliminating the need for chemicals or blasting media.

In addition to laser ablation for surface preparation, laser-assisted cold spray can be effective means for improving cold sprayability (e.g., deposition efficiency) and deposit properties (e.g., bond strength, porosity) [18]. For the hybrid cell, a laser can be used in combination with the commercial spray guns to investigate the effects of localized, high temperature conditions on powder impact on the substrate (e.g., softening and/or melting) with or without the multi-process interactions (machining, ablation, etc.). This type of laser-assisted spray processing can be particularly challenging because it is very difficult to accurately characterize conditions at the target surface (e.g., changing deposit emissivity during the process); process modelling will be critical.

One of the main advantages of cold spray as an additive manufacturing technology is that it is not component size limited. Conversely, one significant constraint when comparing cold spray with laser-based methods, however, is the difference in characteristics of a cold spray spot. The minimum spot size of typical commercial cold spray nozzles is ~4 mm and a profile is obtained across this diameter [19]. Efforts have been made to reduce spot sizes with smaller diameter 'micronozzles', although sizes are still on the order of ~1 mm [20].

Due in part to its inherent spray characteristics, cold spray AM to date has often employed a methodology of rapid material deposition, with or without masking, into relatively simple shapes and wide tolerances that can lead to constraints in part geometries and/or significant post-spray machining. An investigation has been performed into producing more complex geometries and improving shape fidelity through a layer-by-layer approach to build strategy and toolpath planning [21].

The toolpath planning and programming required to build 3d structures with complex geometry and low (overspray) tolerances intrinsically requires precise manipulation of the spray gun, or part as applicable. The build strategy employs a conventional AM strategy; namely, starting with a CAD drawing, slicing the CAD geometry into a layered structure, and performing a layer-by-layer build. A slicing method suitable for cold spray builds can differ somewhat from other conventional AM techniques as cold spray AM can be used to build features on existing parts and the associated spray surface is not necessarily flat. For contoured surfaces, one slicing strategy is to produce a layer spanning the entire surface while another would be to selectively add material where needed until the entire surface becomes essentially flat before proceeding with the rest of the build.

A challenge for more complex features and surfaces is (as previously mentioned) the toolpath and line-of-sight. Although limits are being explored, designs can still be relatively flexible with the use of suitable fixturing and nozzle-substrate positioning during the build. In one example each deposited layer spanned the entire feature footprint on the surface of the substrate. However, additional flexibility can be obtained by initially spraying only areas required to build out the curved surface. Once a (combined deposit and substrate) flat surface is obtained, the remainder of the feature can be built.

One of the attractions of conventional 3D printing oriented AM is the ability to build any component regardless of its complexity. However, the hybrid approach demonstrates a capability to minimize efforts for both cold spraying and machining, and to maximize the benefits of both techniques. For example, a strategy for manufacturing a wheel consisted of the following: (i) select a standard stock size plate that minimized material to be added/subtracted, (ii) build one side (outside of wheel) of the higher thickness hub and rim sections by cold spray, (iii) machine *both* the stock plate and deposited material to match the outside wheel contour, (iv) flip the piece and repeat steps ii-iii for the inner wheel contour [21].

Conclusions

With respect to additive manufacturing, the main similarity with more conventionally recognised AM technologies is that cold spray is fundamentally a powder consolidation technique. As a 'coating' technology, cold spray's potential in additive machining (as opposed to subtractive machining) is currently well recognised and developed. Compared to additive manufacturing techniques centered on 3D printing concepts, the main advantage is that component size is 'unlimited'; the main disadvantage is that cold spray does not have comparable areal resolution of features, even with new developments in 'micro' nozzles. On the other hand, layer by layer build strategies can be implemented, thus increasing the capacity to accomplish more complex builds by cold spray. The key to implementing cold spray additive manufacturing is hybridization, whether it is with laser based technologies, to capitalize on the effect of temperature, or with conventional subtractive machining in order to maximize the strengths of both additive and subtractive machining.

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