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Research Letter

Some Material Characteristics of Cold-Sprayed Structures

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The deposition and consolidation of metal powders by means of cold spray are methods whereby powder particles are accelerated to high velocity through entrainment in a gas undergoing expansion in a rocket nozzle and are subsequently impacted upon a surface. The impacted powder particles form a consolidated structure which can be several centimeters thick. The characteristics of this structure depend on the initial characteristics of the metal powder and upon impact velocity. The influence of impact velocity on strain hardening and porosity are examined. A materials model is proposed for these phenomena, and model calculation is compared with experiment for the cold spraying of aluminum.

1. INTRODUCTION

The cold spray process imparts supersonic velocities to metal particles by placing them in a heated gas stream that is expanded through a converging-diverging nozzle. The particles are directed towards a substrate, where they are embedded, forming a strong bond with the substrate. Subsequent spray passes increase the structure thickness. Structures composed of a wide variety of materials can be produced with good mechanical properties in a short amount of time.

The characteristics that cold spray imparts upon deposited structures are well known [1–4] and include compressive residual stress, low-oxide content, low porosity, and high hardness. While these tendencies are known, descriptive models are lacking. The properties are often explained on an intuitive basis, and all explanations employ impact phenomena. We will combine an impact mechanism with material properties and empirical relationships to describe how the strain hardening and porosity of deposited structures are affected by the particle velocity imparted by the cold-spray process.

2. PARTICLE DEFORMATION

A power-law relationship between stress and plastic strain attributed to Hollomon [5] is employed for particle deformation:

$$\sigma = K\varepsilon_p^n, \tag{1}$$

where σ is stress, ε_p is the plastic strain, K is the material strength coefficient, and n is the material work-hardening exponent. While it does not take strain rate into consideration, this is the simplest and most commonly used strain-hardening equation.

It is assumed that originally spherical particles are flattened to an equal volume ($d_0^3 = d_a^3 d_b$) oblate spheroid shape through impact (Figure 1).

The deceleration force experienced by the particle during impact is given by

$$F = ma = \left(\rho \cdot 4/3 \cdot \pi \cdot (d_0/2)^3\right) \cdot dV/dt \tag{2}$$

dV/dt is equal to the change in velocity, $V - 0 = V$, divided by the stopping time, $(d_0 - d_b)/V$.

If the average stress experienced by the particle is the deceleration force divided by the flattened area, then the stress is given by

$$\sigma = \frac{4\rho V^2}{6(f_r^{\,2} - 1)}, \tag{3}$$

where f_r = flattening ratio = (d_a/d_0).

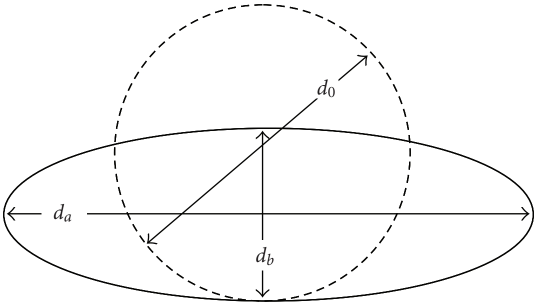

Figure 1: Particle flattening upon impact.

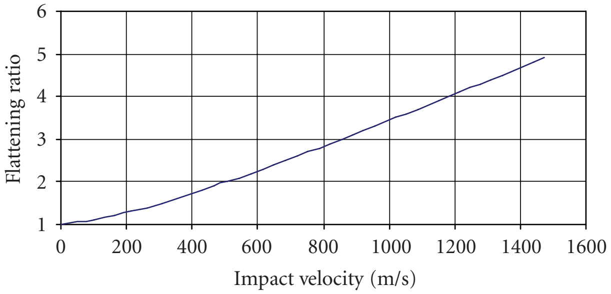

Figure 2: The flattening ratio for aluminum particles as a function of impact velocity.

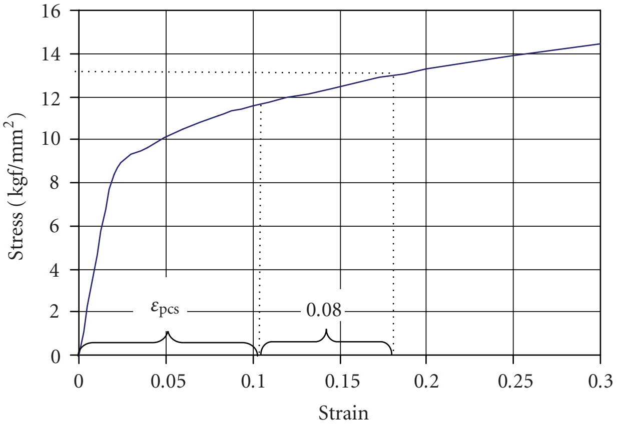

Figure 3: Vickers hardness determination by the tabor relationship.

The plastic strain experienced by the particle is

$$\varepsilon_{\text{pcs}} = \frac{d_0 - d_b}{d_0} = 1 - (d_0/d_a)^2 = 1 - (f_r)^{-2}. \tag{4}$$

By (1), the stress required for this strain is

$$\sigma = K\varepsilon_{\text{pcs}}^n = K(1 - f_r^{-2})^n. \tag{5}$$

Equating (3) with (5), we obtain a relationship between the particle velocity at impact and the degree of flattening:

$$\frac{4\rho V^2}{6(f_r^2 - 1)} = K(1 - f_r^{-2})^n. \tag{6}$$

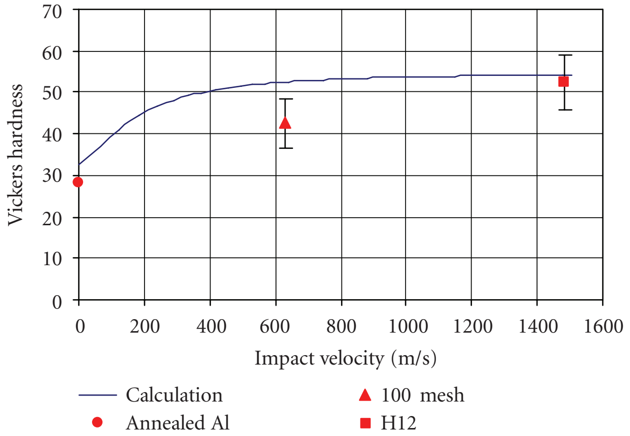

Figure 4: Work hardening of cold-sprayed aluminum.

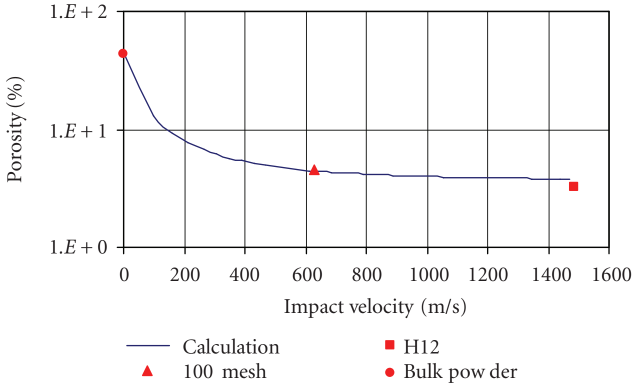

Figure 5: Compaction of cold-sprayed aluminum powder reactivity.

Figure 2 shows the flattening of aluminum as a function of impact velocity, where $\rho = 2.7$ g/cc, $K = 180$ MPa, and $n = 0.2$ [6].

3. STRAIN HARDENING

Strain or work hardening of a cold-sprayed structure is caused by the plastic deformation of particles that have impacted with and have subsequently been incorporated into the structure. Changes in hardness can be estimated from knowledge of the particle deformation upon impact.

When measured by a Vickers indenter, Tabor [7] has shown that the hardness number is given by the empirically determined equation

$$\text{HV} = 3\sigma_{0.08}, \tag{7}$$

where $\sigma_{0.08}$ = stress at a plastic strain of 0.08.

Figure 3 shows a plot of (1) for aluminum ($K = 180$ MPa and $n = 0.2$). An imparted plastic strain following impact ε_{pcs} is shown. The stress that would give an additional strain of 0.08 is also shown.For the example shown, the Vickers hardness given by (7) is HV $= 3 \times 13 = 39$, which is typical for pure aluminum.

For a cold-sprayed structure, $\sigma_{.08}$ is given by (1) and (5) as in

$$\sigma_{0.08} = K(\varepsilon_{\mathrm{pcs}} + 0.08)^n = K[(1 - f_r^{-2}) + 0.08]^n. \tag{8}$$

4. POROSITY

A powder metallurgy equation, relating relative density with applied packing pressure, shows how the porosity of a cold-sprayed structure is related to impact velocity. The Heckel equation is [8]

$$\ln\left(\frac{1 - D_0}{1 - D}\right) = K_H P, \tag{9}$$

where D = density relative to wrought density, ρ/ρ_w, D_0 = bulk powder relative density, ρ_0/ρ_w, K_H = a constant equal to the inverse of the wrought material yield strength, σ_y, and P is compaction pressure. Solving this equation for D,

$$D = 1 - (1 - D_0)\exp(-P/\sigma_y). \tag{10}$$

At this point, we assume that the compaction pressure is equal to the pressure exerted through particle impact and is thus equal to σ of (5). This assumption, along with the definition of percent porosity as equal to $100(1 - \rho/\rho_w)$, gives

$$\%\mathrm{porosity} = 100(1 - \rho_0/\rho_w)\exp\lfloor -K(1 - f_r^{-2})^n/\sigma_y\rfloor. \tag{11}$$

5. EXPERIMENTAL

Two aluminum powders of significantly different size distribution were cold-sprayed onto an aluminum surface for analysis and comparison with the developed models. The powders were manufactured by the Valimet Corporation (Calif, USA) and are designated as H12, and 100 mesh. The powders contain a minimum of 99.7% weight aluminum. The size distributions of these powders, determined by Horiba LA-910 analyzer, yielded median particle diameters of 14 and 114 μm for the H12 and 100 mesh, respectively. The cold-spray process accelerates small diameter particles to higher velocities than larger diameter particles; hence the mean particle velocity for H5 particles is 1485 m/s, while that of 100 mesh is 629 m/s.

Blocks of these powders (2 cm × 2 cm × 0.5 cm) were deposited on aluminum substrate for characterization. The hardness of the deposits was measured with a tukon series B200 microhardness tester. Eight measurements were performed on each of two perpendicular planes, with the high and low readings discarded. The hardness value was an average of the remaining twelve readings. In addition, the hardness was calculated by means of (6), (7), and (8). The results of these measurements and calculations are shown in Figure 4. The annealed hardness is taken from [9].

The porosities of the deposits were measured through liquid displacement. In addition, the porosities were calculated by means of (6) and (11). The results of these measurements and calculations are shown in Figure 5.

6. DISCUSSION

A relatively simple particle impact model applied to well-known material characterization equations has been shown to result in good prediction of the hardness and porosity resulting from the cold-sprayed deposition of aluminum. A model employing the Hollomon strain-hardening equation yields results close to experimental results. Similarly, a model employing the Heckel compaction equation yields porosity predictions that are close to experiment. Cold-spraying aluminum resulted in up to a two-fold increase in Vickers hardness of the deposit and a reduction of porosity from a bulk value of 44% to less than 3%.

Many simplifications are employed in the modeling effort. Temperature effects are not addressed, nor are the variations of particle size within a given powder. Strain rate was also not considered. Efforts will be made to account for these effects in future work; however, the simple model presented allows an understanding of the phenomena that lead to changes in hardness and porosity of cold-sprayed structures.

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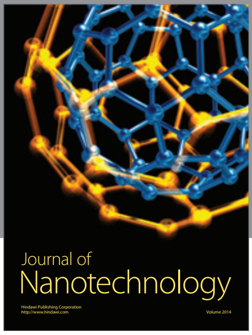
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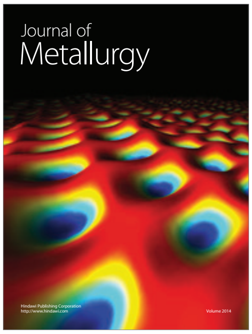
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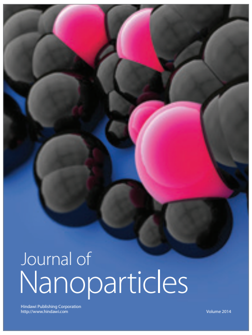
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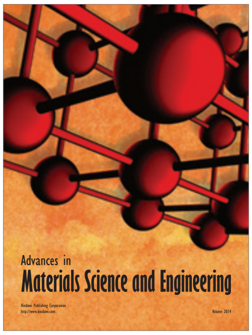
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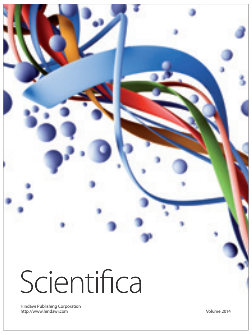
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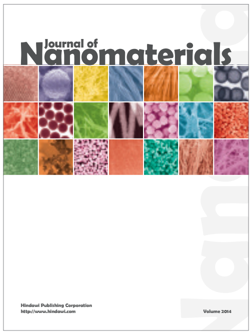
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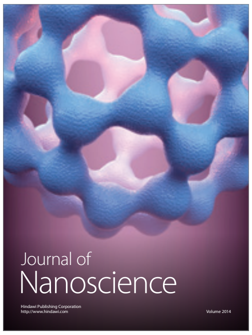
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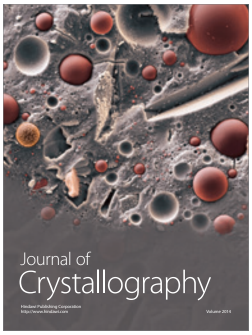
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