SCALING ANALYSIS OF THE ELECTROMAGNETIC POWDER DEPOSITION GUN

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Abstract

The electromagnetic powder deposition (EPD) system employs high velocity gas flow to accelerate powder material to conditions required for high strength plating. The gas flow, however, is not continuous; rather it consists of bursts generated by an electromagnetic railgun and pulsed power system. Each gas burst is created by a high pressure plasma arc which fills a transverse section of the gun. This current carrying arc is driven by the railgun Lorentz force (magnetic pressure) and acts much like a piston, which via a snowplow process accelerates and compresses an ambient gas column to the flow speed required to accelerate powder particles.

Analysis of the total system was carried out to provide scaling relations which give guidance in design of the system. Plating considerations define a desired powder velocity; this combined with the choice of working gas and ambient pressure determines the velocity and duration of each gas burst. Selection of gun geometry completes the definition of the pulsed power system requirements. An outline of the analysis is presented along with the physical models used.

THE EPD PROCESS WAS DEVELOPED as a method of imparting high velocities to powder particles for creation of high mechanical strength surface platings. Like other coating processes, the high particle velocity is achieved by flowing supersonic gas past the particles; the viscous drag force associated with such flows is the mechanism used to accelerate the particles to desired final velocity. What is unique to the EPD approach is that use of electromagnetic railgun force means that the gas flow velocity can be as high as desired, and is not limited by any chemical or thermodynamic constraints. The railgun process is combined with a gasdynamic mechanism, called a snowplow, to produce controllable bursts of gas with the speed and duration required to accelerate finite segments of dispersed powder to the conditions required for plating purposes.

Powder Acceleration - General Considerations

Gasdynamic generated viscous drag has a long history of use as a means of accelerating particles to high velocity. To apply simple theory to the design of our system, the assumption is made that the powder of interest is so finely dispersed that particles are far apart and the gas flow around any one particle is not affected by other particles. When this holds, the time and length scales for the gas flow are defined by the dynamics of a single particle. Again for simplicity, the process is taken to be one dimensional, which is a good approximation for describing the physical mechanisms involved, and is in fact a very good approximation to the actual system design.

Each powder particle is assumed to be a solid sphere of diameter D_p and density ρ_p. Gas of density ρ_g and (constant) velocity V_g streams by each particle. The force equation [1] is

$$M_p \frac{dV_p}{dt} = C_D A_p P_k \qquad (1)$$

where

M_p = powder particle mass $= \frac{\pi}{6} \rho_p D_p^3$

V_p = powder particle velocity

C_D = drag coefficient

$$A_p = \text{powder particle projected area} = \frac{\pi}{4} D_p^2$$

$$P_k = \text{gas kinetic pressure} = \frac{1}{2} \rho_g (V_g - V_p)^2$$

The drag coefficient C_D which appears in equation (1) is, in general, a function of both gas and particle velocity. From empirical data on supersonic flow[1] it is known that this parameter is close to unity for a wide range of Mach numbers ≥ 1. For design purposes we assume that $C_D = 1$ at all times.

It is convenient to work with dimensionless variables. Define the following new variables :

$$f = \frac{V_p}{V_g} \quad \text{and} \quad \xi = \frac{t}{\tau}$$

where

$$\tau = \frac{4}{3} \frac{1}{C_D} \frac{\rho_p}{\rho_g} \frac{D_p}{V_g}$$

Then equation (1) takes the form

$$\frac{df}{d\xi} = (1 - f)^2 \tag{2}$$

which yields the solution

$$f = \frac{\xi}{1 + \xi} \tag{3}$$

Using equation (3) in equation (2) gives the dimensionless acceleration

$$a = \frac{df}{d\xi} = \frac{1}{(1 + \xi)^2} \tag{4}$$

Another quantity of interest is the length of gas column needed to accelerate a particle for a time ξ. This is derived by working in a reference frame moving with the particle. The apparent gas velocity is this frame is

$$V_g' = V_g - V_p = V_g (1 - f) = \frac{V_g}{(1 + \xi)} \tag{5}$$

The "normalized" length of gas column seen by a particle is

$$l' = \frac{l_g}{V_g \tau} = \frac{\int V_g' dt}{V_g \tau} = \int \frac{d\xi}{(1 + \xi)} = \ln(1 + \xi) \tag{6}$$

Figure 1 shows these particle parameters of interest - velocity, acceleration, and gas length - plotted as a function of normalized time.

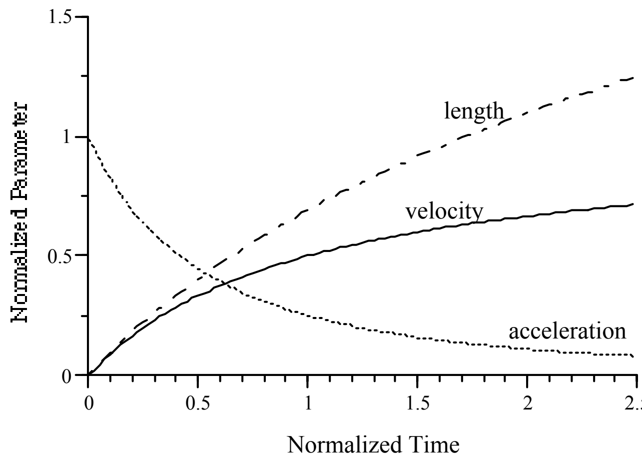

Figure 1 - Normalized parameters of interest

The trend of the curves in Figure 1 indicate that little is gained by accelerating for more than one normalized time period. During this interval the particle is brought to one-half the gas speed; acceleration at this point has fallen to one quarter of the initial value and is rapidly decreasing with increasing time. The design choice has been made to work with one normalized time period. Setting $C_D = 1$, this gives a duration

$$\delta t = \tau = \frac{4}{3} \frac{\rho_p}{\rho_g} \frac{D_p}{V_g} \tag{7}$$

while the length of gas column needed to accelerate powder is

$$l_g = 0.9242 \frac{\rho_p}{\rho_g} D_p \tag{8}$$

The relevant scaling point is that the length of gas column needed scales linearly with particle size and inversely with the gas density, with the gas burst duration having the same scaling but also dropping inversely with gas speed. To keep system size small it is desirable to use small powder size and high velocity, high density gas.

Gas Flow Generation - General Considerations

Having defined the parameters required of the gas bursts to be used for powder acceleration, the next task is to design a process for creating them. A plasma armature railgun technique [2] studied two decades ago has been selected for generating high density supersonic gas flow. A schematic of the concept is shown in Figure 2.

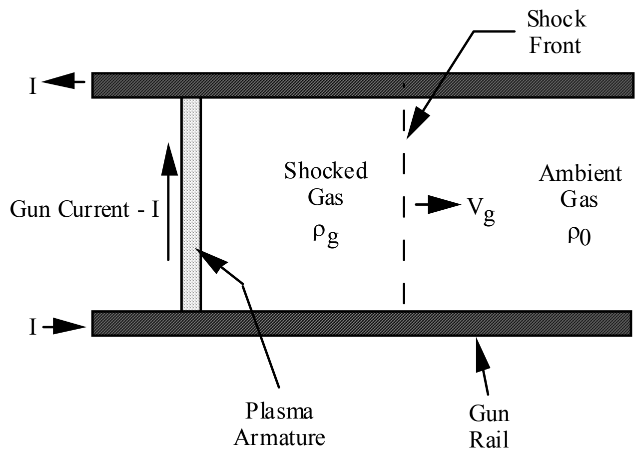

Figure 2 - Schematic of railgun snowplow system

The railgun consists of two metallic rails with insulating sidewalls separating them. A low mass plasma armature, formed from the ambient gas, is used to commute the gun current between the rails. This configuration generates a magnetic field within, and to the left of, the armature. The current carrying ions and electrons of the plasma experience a net Lorentz force which accelerates the whole armature to the right down the gun bore. The armature is generated in such a way that it fills the entire transverse area of the bore. As it is accelerated to the right, it collisionally interacts with the ambient gas in the bore and accelerates it to the same velocity. This is the essence of the snowplow. The arc armature acts like a piston, scooping up gas as it moves down the gun bore.

Gun current and bore dimensions are chosen to ensure that the armature velocity very quickly exceeds the sound speed in the ambient gas. Because of this, the gas scooped up by the snowplow process generates a shock front which propagates down the gun. The gas accumulated by the snowplow process is compressed to a higher density than the ambient gas. Also, the velocity of the shock front slightly exceeds the velocity of the armature/gas column system. Formulas for computing the compression ratio and shock speed are readily available [3]. The sound speed in the ambient gas is denoted by c_S.

Call the coordinate along the gun axis the Z direction. The local force balance equation of magnetohydrodynamics [4] can be integrated over the volume of both the armature and snowplowed gas column to give the equation

$$\frac{d}{dt}(M V_g) = \frac{1}{2} L' I^2 \qquad (9)$$

where

M = mass of armature / gas column system

$V_g = \frac{dZ}{dt}$ = velocity of armature / gas column system

L' = inductive gradient of railgun

I = gun current driving the armature / gas system

The gun current is determined by the electrical circuit driving the system. For maximum acceleration, take the gun current as constant. Then equation (9) is integrated to give

$$M V_g = \frac{1}{2} L' I^2 t \qquad (10)$$

If the mass of the armature is denoted M_A, and does not increase with time, then the mass of the armature/gas column system after the armature has moved a distance Z is, to good approximation,

$$M = M_A + \rho_0 A Z \qquad (11)$$

where

ρ_0 = density of ambient gas

A = area of gun bore cross section

Putting equation (11) in equation (10) and integrating, the solution for position versus time is

$$\rho_0 A Z^2 + 2 M_A Z = \frac{1}{2} L' I^2 t^2 \qquad (12)$$

Setting

$$Z_A = \frac{M_A}{\rho_0 A}$$

the explicit solution is

$$Z = \sqrt{Z_A^2 + \frac{L' I^2}{2 \rho_0 A} t^2} - Z_A \qquad (13)$$

The general nature of the solution is that very quickly the armature/gas column system reaches a terminal velocity given by

$$V_g = I \sqrt{\frac{L'}{2 \rho_0 A}} \qquad (14)$$

Physically what this means is that the railgun driving force in equation (9) is being used to snowplow up, and compress, ambient gas at a constant velocity V_g. Said another way, at constant velocity the time derivative of equation (11) can be used in equation (9) to give

$$\rho_0 A V_g^2 = \frac{1}{2} L' I^2 \qquad (15)$$

which is formally identical to equation (14).

The gas compressed by the snowplow process is used to accelerate powder particles. For design purposes it is necessary to know the density of the compressed gas. To compute this, the strong shock limit[3] can be used to good approximation. In this limit, $V_g >> c_S$, the compression ratio is

$$\frac{\rho_g}{\rho_0} = \frac{\gamma + 1}{\gamma - 1} \qquad (16)$$

where

$$\gamma = \frac{C_P}{C_V} = \text{specific heat ratio for the plasma}$$

Plating Systems - Specific Example

Details of the EPD design depend on the velocity chosen for the powder particles. General trends in plating strength suggest that velocities exceeding 1 km/s are worthy of study. To quantify the design, and allow a wide range of velocity to be explored, we have chosen to focus on particle speeds which correspond to specific kinetic energies which are equivalent to double the specific energy needed to completely melt the powder material. That is, if the kinetic energy can be converted to purely thermal energy, then each particle has an energy which is twice its latent heat of fusion. For materials of interest, such as titanium or Inconel or chromium, this gives

$$\text{Specific K. E.} = \frac{1}{2} V_P^2 = 2 \Delta H_{fusion} \approx 2.2 \text{ kJ / g} \qquad (17)$$

or

$$V_P \approx 2.1 \text{ km / s} \qquad 18)$$

From our choice of one normalized unit of acceleration time, the corresponding gas velocity is

$$V_g \approx 4.2 \text{ km / s} \qquad (19)$$

Because oxidation of plating material is to be avoided, we have selected argon gas at atmospheric pressure as our working medium. At NTP its density is 1.78 mg/cm^3. We here consider the powder material to be Inconel, with density of 8.3 g/cm^3. The typical powder diameter is taken to be 100 µm. Also, use is made of the fact that for argon at high temperatures the specific heat ratio is about γ = 1.4. Enough information is now available to size the EPD system.

From equation (16) the density of the shock compressed argon is

$$\rho_g = \left(\frac{\gamma - 1}{\gamma + 1}\right) \rho_0 = 6\ \rho_0 = 0.0107 \text{ g / cm}^3 \qquad (20)$$

Equation (8) gives for the length of the shock compressed gas

$$l_g = 7.2 \text{ cm} \qquad (21)$$

Because this column is created by a snowplow process which gives a factor of 6 density compression, the length of the railgun is this density factor times the gas length, i.e.

$$L_{gun} = 43.0 \text{ cm} \qquad (22)$$

Viewed as a sequential combination of railgun plus powder accelerator, the overall system length is then

$$L_{system} = L_{gun} + l_g \cong 50 \text{ cm} \qquad (23)$$

which represents a fairly compact unit.

The pulsed power aspects of the system are next addressed. Recalling that the snowplow process rapidly reaches terminal velocity, then equations (22) and (19) are used to estimate the duration of the constant gun current required. These give

$$T_{gun} = \frac{L_{gun}}{V_g} \approx 120 \ \mu\text{s} \qquad (24)$$

Equation (14) is used to estimate the gun current required. Here the actual gun geometry becomes very important. The scaling of equation (14) suggests that to keep the current low one wants to keep the bore area small while maintaining a high inductance gradient. A square bore geometry is the only viable choice. By exploiting our past experience in railgun design, we have selected

$$A = \frac{1}{2} \text{ in.} \times \frac{1}{2} \text{ in. square bore} \Rightarrow A = 1.613 \text{ cm}^2 \qquad (25)$$

$$L' \cong 0.5 \frac{\mu H}{m} \qquad (26)$$

Combined with other design parameters, this yields

$$I = V_g \sqrt{\frac{2 \rho_0 A}{L'}} \approx 150 \text{ kA} \qquad (27)$$

The gun represents a time varying electrical load having both resistive and inductive components. The resistive part represents both electrical skin depth effects and the resistance of the current carrying arc. It can be approximated by the relation

$$R = R_{arc} + R' Z \tag{28}$$

where the skin depth part (copper rails are assumed) is

$$R' \cong \sqrt{\frac{2 \mu_0 \eta}{A T_{gun}}} \approx 1.76 \text{ m}\Omega / \text{m} \tag{29}$$

The inductive part also scales linearly with distance

$$L_{gun} = L' Z \tag{30}$$

The voltage generated at the breech of the gun is then

$$V = R I + \frac{d}{dt}\left(L' Z I\right) = \left(R + L' V_g\right) I \tag{31}$$

where use is made of the constant current approximation and the fact that the terminal velocity is quickly reached. To high order, the gun looks electrically like a ***pure*** resistive load equal to

$$R_{gun} = R_{arc} + R' Z + L' V_g \tag{32}$$

The inductive component appears resistive because of the constant velocity of the railgun snowplow process. Numerically it is equal to 2.1 mΩ. Only near the end of the electrical pulse does the skin depth resistance approach 1/2 of the inductive term. Experimentally it is found that the arc resistance is fairly constant, with a value of 1 mΩ for cases of interest here.

The pulsed power system required is one which will provide a constant 150 kA current for 120 µs. It must drive a railgun load that is approximately 2 to 3 mΩ in resistance. In addition, the plasma armature will appear as a resistive load equal to 1 or 2 mΩ. The ideal way to achieve this performance is to use a low impedance transmission line whose one-way electrical length is 60 µs. In practice, this is approximated by a pulse forming network (PFN) constructed of LC (inductive-capacitive) circuits in parallel. A four stage design for the PFN has been carried out. Because the railgun with snowplow load represents such a low impedance, realizing a fast current rise time is difficult to achieve without going to a PFN design that has an equivalent impedance of about 26 mΩ. Figure 3 shows the gun current expected from this design; the waveform was generated using a finite difference computer code developed for studying PFN optimization and system performance.

Figure 3 - Gun current generated by PFN circuit

Plasma Armature - Instability Considerations

To operate in the snowplow mode, the railgun armature must maintain a planar form filling the bore cross-section during the entire acceleration time. Because the armature is a gaseous plasma, not a solid, instabilities could potentially be a major difficulty. Two specific instability mechanisms have been studied because they are known to be important in other plasma arc applications. The physical situations are discussed, and analytic results presented for these two cases.

The first mechanism considered is called the filamentation, or thermal runaway, instability. It arises physically from two phenomena: the first is the fact that parallel currents attract each other, so the arc current flow wants to pinch naturally. The second is the fact that the resistivity of a plasma falls as the plasma temperature is increased (Spitzer resistivity). The attraction of parallel current elements in the arc tends to be balanced by internal gas pressure, and is not the major driving mechanism here. The analysis then focuses on the thermal runaway aspect of the problem. Considering a general element of the arc, the energy balance equation can be written as

$$\rho C_p \frac{\partial T}{\partial t} = \dot{Q}_{in} - \dot{Q}_{out} = \eta J^2 + \vec{\nabla} \cdot (k \vec{\nabla} T) \tag{33}$$

where the first term on the RHS represents ohmic heating per unit volume by current flow in the plasma, and the second term represents the rate of energy loss per unit volume by “thermal conduction”. Equilibrium corresponds to no time rate of change in the temperature, i.e. setting (33) equal to zero. This yields an equation which can be solved given the thermo-physical properties of the armature plasma. The results are well known in railgun work [4], and correspond to plasma temperatures of about 2 eV, i.e. 20,000°C. If equation (33) is linearized about equilibrium, then stability is assured if the resulting equation is less than zero. As noted, the resistity of the plasma falls with temperature, roughly as the inverse of the temperature to the 3/2 power. For normal heat conduction, the thermal conductivity - k - has a weak temperature dependence.

However, for the dense plasmas of interest here, heat conduction is by black body radiation, and the effective conductivity scales roughly as the third power of temperature. When these scalings are used in the linearized version of equation (33), stability is seen to occur. Thus for armatures used for the EPD railgun the filamentation instability is not a problem.

The second mechanism addressed is called the Rayleigh-Taylor instability; it is a generic problem which occurs when a light fluid (here magnetic field) is used to accelerate (support) a heavier fluid (here plasma). A good example of this instability is the attempt to support mercury on top of water in a container. This physical state can in fact be realized, but common experience shows that any small perturbation to this system quickly leads to a state with the mercury on the bottom and the water on top. As applied to the EPD process, the worry is that the magnetic field would try to slip past the plasma, leaving plasma filaments behind. The growth rate for such a case is estimated to be

$$\Omega_{RT} \approx \sqrt{\frac{a}{w}} \approx \frac{1}{10\ \mu s} \tag{34}$$

where a is the acceleration generated by the railgun, and w is the plasma arc length. Physically, however, the magnetic field cannot rush past the current which is generating it, but must diffuse through the conducting medium. With a diffusion growth rate given by

$$\Omega_{diff} = \frac{\eta}{\mu_0 w^2} \approx \frac{1}{3\ \mu s} \tag{35}$$

then a detailed analysis has shown that the combined growth rate is

$$\Omega \approx \frac{\Omega_{RT}^2}{\Omega_{diff}} \approx \frac{1}{33\ \mu s} \tag{36}$$

This estimate suggests that with an EPD railgun pulse time of about 100 μs, this instability will have no more than 3 e-folding times to grow from low levels, and thus should not be a major problem.

Experimental Test of the EPD Process

Experimental tests have been carried out at the Center for Electromechanics to explore the EPD concept. A simulation code was developed to provide experimental guidance, and also to serve as a tool in interpreting the data. The test bed consisted of a 0.5 m long square bore gun with 1.6 cm^2 area, driven by a simple inductor-capacitor (LC) energy store. A glow discharge arc initiator was developed to provide a well defined armature. A battery of magnetic probe, fiber optic, and pressure transducer diagnostics were used to characterize the experiments. A fast CCD camera was also used to obtain particle velocity. The arc initiator and diagnostic development are discussed in other papers in this conference. Here a discussion of the salient results will be presented.

The LC energy store supplied a sinusoidal current pulse for acceleration of the snowplow. On each discharge the battery of diagnostic data was digitized and stored on hard disk for later analysis. The signals from the various probes could be used to construct a space-time plot for motion of the arc plus shock compressed gas column down the railgun bore. Results of data from five shots is shown in Figure 4.

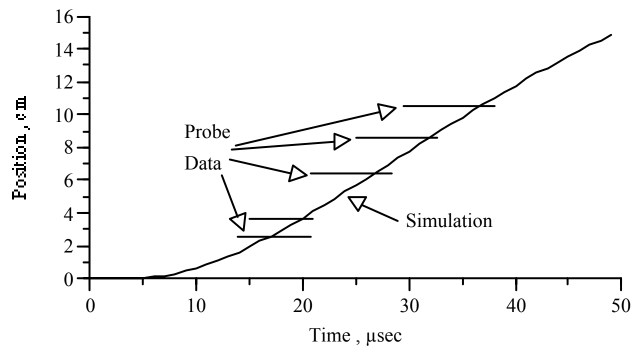

Figure 4 - Arc position versus time

The solid line shows the predicted motion using our simulation code; the probe signals represent time bands at fixed locations. The most probable time for arc armature passage is at the right of the bands, near the code prediction. Since the simulation explicitly assumes that a snowplow process is occurring, the excellent agreement gives strong evidence that the EPD process is operative. From the probe data one can also construct average velocity versus time points to compare with prediction. This is shown in Figure 5.

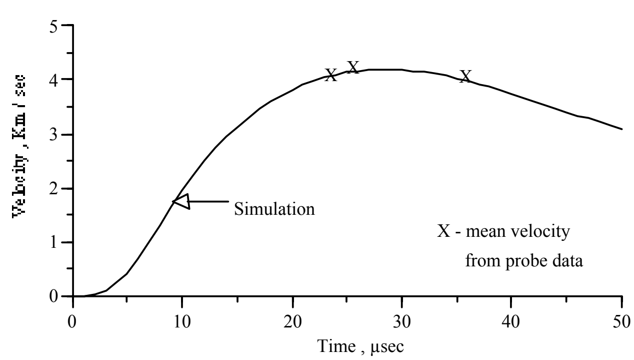

Figure 5 - Arc velocity versus time

Again good agreement is observed. Finally, to verify that such gas flow will accelerate powder particles, insertion of 300 micron diameter, 43 μg mass glass spheres into the gas flow was performed. The glass spheres were started with zero velocity, that is they were initially at rest. The simulation code predicted that the final velocity should be 0.625 km/s. A fast CCD framing camera, rented from Hadland Corporation, was used with 1 µs interframe delay to photograph the spheres. Figure 6 shows two consecutive frames from one shot (similar data was obtained on many shots).

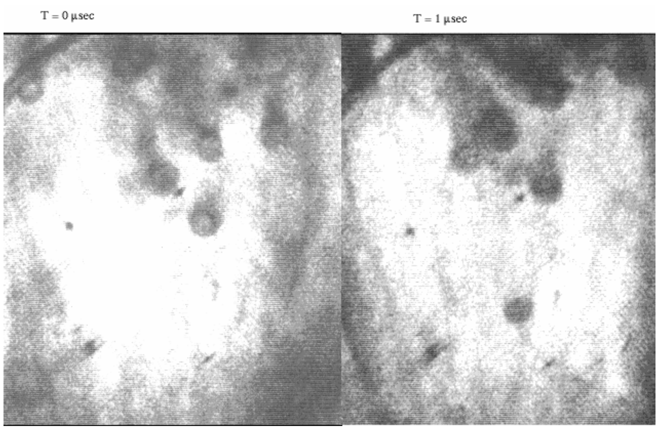

Figure 6 - Photographs of spheres at 0.6 km/s

The Hadland camera system indicated the spheres had a mean velocity of 0.6 km/s, in agreement with code results.

Based upon our present experimental data, design of a higher velocity system - realized mainly by using an improved PFN circuit to drive the railgun - is presently nearing completion. With this system, powder of 100 micron size is expected to reach velocities exceeding 2 km/s.

Acknowledgment

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