The Electrostatic Application of Powder for Selective Laser Sintering

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Abstract

The electrostatic powder application system is designed to deliver powder to the work area in even well packed layers. It delivers the powder from a storage container using compressed air, forces the particles through an electric field, and sprays them onto a grounded plate. A qualitative experiment into the feasibility and performance of the system is presented. A model of the particle charging mechanism, and the particle charge draining mechanism is also presented. The experiment finds that a 20 mill layer of packed powder is repeatedly achievable, and that the system has powder clogging problems.

Introduction

The electrostatic powder application system is intended to replace the current roller feed mechanism in the selective laser sintering process. The electrostatic system should help to create better packed powder layers, reduce the work space requirements, and allow the powder to be stored in a different environment from the work space prior to the application and sintering process. These factors should help to increase the quality of the sintered part by reducing the number of air pockets in the work piece, and by helping to keep applied layers even.

Theory

A theoretical model of the electrostatic powder application process has been derived to determine if the desired effects are being produced at the particle level. Several assumptions have been made to produce a simple closed form model of a traveling charged particle. First, it has been assumed that the particles are spherical. Second, the modeled particle will be in the center of the flow. Finally, the grounded work plate is assumed to be a perfect conductor, and any previously applied powder layers are charge neutral. The resulting model will be able to describe how the particles are influenced, but the magnitudes of the results should be considered suspicious and only used to compare particles and materials, not for prediction of physical behavior.

The capacitance of the material particle is needed to determine the charge that is held by the particle, to resolve the force on the particle, and to determine the time needed for the charge to drain from the particle after the particle has been applied. A model is derived from the basic Maxwell's equations:

$$C = 4\pi\varepsilon_0 R \quad (1),$$

$$Q = V4\pi\varepsilon_0 R \quad (2).$$

These equations yield the capacitance of, and the charge on a given particle.

The electrostatic force that is generated by the charged particle is calculated using the method of images. The method finds the radial and tangential components of the electric field to produce the field in the normal direction:

$$\vec{E}_n = \vec{E}_r \cos\theta - \vec{E}_\theta \sin\theta = \frac{2QD}{4\pi\varepsilon_0 r^3}\hat{E}_n \quad (3).$$

This expression for the electric field can be used to calculate the force that is acting upon the charged material particle, refered to here by its charge Q:

$$\vec{F}=Q\vec{E_n} \quad (4).$$

The radius of the system is known, r=2D, and can be substituted into equation 3, the result of which can be substituted into equation 4 to produce an expression of the electrostatic force upon the particle:

$$\vec{F} = \frac{Q^2}{16\pi\varepsilon_0 D^2}\hat{E}_n \quad (5).$$

A particle that is traveling between the spray head and the work plate is influenced by the electrostatic force, the drag force of the fluid, gravity, and the force of the fluid stream. The gravity force is simply the mass multiplied by the gravitational constant, while the electrostatic force was derived previously. The fluid stream force occurs in the applicator system, not the area between the feed head and the work plate. Assuming that the particle velocity is the same as the fluid velocity at the time of exit from the spray nozzle, the fluid imparts an initial momentum upon the particle equal to the product of the fluid velocity and the particle mass. All particle particle interaction forces are assumed to have a resultant vector of zero.

The particle traveling through the air is also acted upon by a fluid drag force from the air around it, which is proportional to the difference between the particle velocity, and the velocity of the air around it.

$$F_d = \frac{1}{2}\rho A^2 C_D(\Delta V)^2 \quad (6).$$

All of the forces can then be summed to produce a model of the influences upon the particle:

$$\vec{F} = \frac{Q^2}{16\pi\varepsilon D^2}\hat{E}_n - \frac{1}{2}\rho A_p C_D(\Delta V)^2\hat{V} + m\vec{g} \quad (7).$$

The next step is to create an expression for the velocity from the force equation. To create the velocity expression, first, the force equation will be divided by the mass of the particle, then the constants in the equation will be lumped together into three constants a, b, and c. This yields a simple expression for the acceleration of the particle:

$$\vec{a}(x) = \frac{b}{x^2} + c + d\dot{x}^2 \tag{8}$$

This equation has two nonlinearities in it due to the component contributed by the drag force, and the component due to the electrostatic force, thus eliminating the possibility of a closed form solution to this problem. However, the drag force does not necessarily make a significant contribution to the acceleration of the particle, because it depends upon on the difference between the velocity of the air it is traveling with and the velocity of the particle itself. This difference is not going to be large because the particle only travels a small distance between the spray head and the work plate, not allowing the difference to increase rapidly. The drag force term can then be dropped from the system model without losing unacceptable generality or detail:

$$\vec{a}(x) = \frac{b}{x^2} + c \tag{9}$$

The velocity of the system can be found using simple dynamics. The velocity as a function of particle position will be integrated up from the acceleration expression:

$$\ddot{x} = \frac{dv}{dt} = \frac{dv}{dx}\frac{dx}{dt} = v\frac{dv}{dx} \tag{10}$$

$$\int_{x_0}^{x} \left(\frac{b}{x^2} + c\right) dx = \int_{v_0}^{v} v\, dv \tag{11}$$

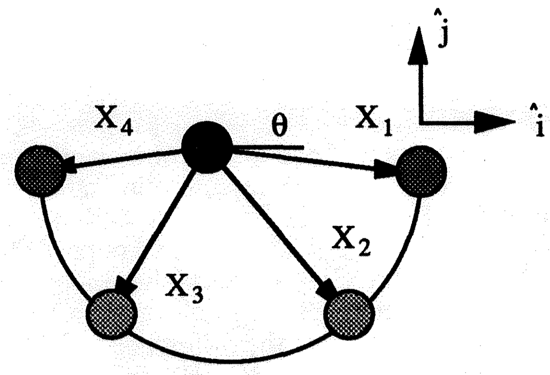
This expression is now integrated to obtain an expression for the velocity of the particle :

$$v^2 = v_0^2 - 2(x - x_0)\left[\frac{b}{xx_0} + c\right] \tag{12}$$

The initial velocity is the velocity of the charged particle at the exit of the spray nozzle, and initial position of the particle is the vertical displacement at the exit of the spray nozzle.

Once the particle has landed upon the work surface, the charge will be drained to ground. This system can be thought of as a simple current driven RC circuit. The resistance and capacitance of the layers is needed to describe the charge dissipation, realizing that different values of these terms are present due to the state of sintering and the presence of boundary conditions.

An important reason for this theory is the hypotheses that a charged particle in flight will tend to fill in a valley. The model that is derived here assumes that the valley is a two dimensional cup, and that the charge on the walls of the valley can be approximated by four point charges with charge of the same sign as the particle's. This model is an excellent approximation because the walls of the cup consist of discrete charged particles. This model assumes that all of the particles, those in the valley and the travelling particle, are being applied during the same feed head stroke.



Particle approaching a Valley
Figure 1

The charge on the particles in the cup wall will be different due to the difference in the time between impact of the particles, and the difference in the powder thickness below them. An expression of their charge is:

$$q_1 = q_4 = Q_0 e^{-\frac{t_1}{RC}} \quad (13),$$

$$q_2 = q_3 = Q_0 e^{-\frac{t_2}{RC}} \quad (14),$$

where t2>t1. The force acting upon the travelling particle by the four charged particles in the wall of the cup is:

$$\vec{F}_{nQ\hat{X}} = \frac{-q_n Q}{4\pi\varepsilon_0 \vec{X}_n^2} \cos\theta_n \hat{i} \quad (29),$$

$$\vec{F}_{nQ\hat{Y}} = \frac{-q_n Q}{4\pi\varepsilon_0 \vec{X}_n^2} \sin\theta_n \hat{j} \quad (30).$$

An example using numerical values in equation 7 is worked using values for nylon 6 and alumina. Both of these materials have been sintered. The values used in the equation are from reference material containing information about these two materials. These numbers can be substituted into simplified equation 7, and produce a numerical representation of the interaction between the plate and the particle:

$$\vec{F}_n = -\frac{1.80 \times 10^{-10}}{D^2}\hat{j} - 4.69 \times 10^{-8}\hat{j} \quad (31),$$

$$\vec{F}_a = -\frac{4.55 \times 10^{-10}}{D^2}\hat{j} - 1.11 \times 10^{-7}\hat{j} \quad (32).$$

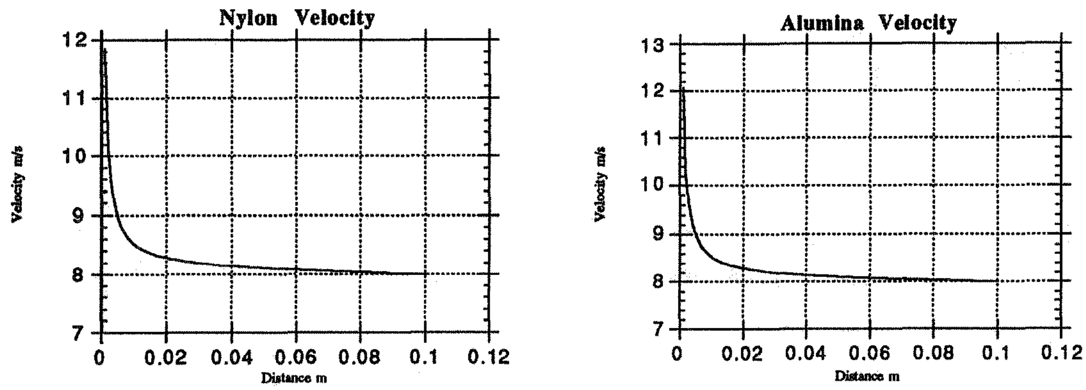


Figure 2

It has been assumed that the velocity vector is in the negative Y direction, and the electric field is in the negative Y direction. The distance between the spray nozzle and the work plate is set at 10 cm for the simulation, and is the initial value of the displacement x. The initial velocity is one that was typically used in the experiment. The final value of the displacement was 0.1 mm. The results of the velocity simulation are graphed in figure 2.

The velocity of both the alumina and the nylon particle theoretically approach infinity. The acceleration of the particles at a distance of 1 mm from the work surface is 39 g for the nylon particle, and 42 g for the alumina particle. This large increase in the acceleration of the particles begins at a distance of 7 mm from the surface of the work plate, a distance of approximately 35 particle diameters from the work surface.

The following example illustrates the forces acting upon the charged particle when the particle approaches a valley of charged particles. The values of resistance and capacitance for the charged layers of material were chosen based on the layer thickness of the real particle layers, and known sizes of capacitors and resistors making a reasonable approximation of the contribution of the air gaps between particles to the resistance and capacitance of the material. The positions of the charged particles were chosen by placing them in a hemisphere of radius 0.005 m, and placing the travelling particle at the point 1 mm to left of the center, and 1 mm above the semicircle. It is assumed that the particle has momentum only in the negative Y direction when it is at this point. Two values of time are used to compute the charge on the particles in the valley, and the values are based upon the particle velocity.

These numbers were put into equations 29 and 30 and summed over the particles. For the nylon system, the numbers are:

$$\vec{F}_n = 1.82 \times 10^{-5}\hat{i} + 4.69 \times 10^{-5}\hat{j}\,\mathrm{N} \quad (33),$$

$$\vec{a}_n = 3{,}807.5\,\hat{i} + 10{,}376.5\,\hat{j}\,\frac{m}{s^2} \quad (34).$$

The alumina numbers are much smaller:

$$\vec{F}_a = 1.23 \times 10^{-7}\hat{i} + 0.90 \times 10^{-7}\hat{j}\,\mathrm{N} \quad (35),$$

$$\vec{a}_a = 10.9\,\hat{i} + 7.96\,\hat{j}\,\frac{m}{s^2} \quad (36).$$

It can be seen that nylon, which has a larger electrical time constant, will be influenced much more than alumina.

Experiment

An electrostatic powder application system was constructed and tested to determine if the desired physical phenomena were present. The apparatus consisted of a powder canister which holds and delivers powder similar to an aerosol can, flow control devices that regulate compressed air flow into the powder canister and the air flow that carries the air from the powder canister to the feed head. The powder leaves the canister and enters the feed head, which is mounted on a linear actuator rated at 20 ips. The feed head turns the flow from vertical to horizontal, forces it through a spray nozzle, and electrostatically charges the powder. The powder is charged in the spray nozzle with two 13.5 kV, 0.31 mA power sources, one delivering positive charge the other negative. A set of valves were inserted in the line between the feed head and the powder canister to bleed most of the powder flow off in an effort to prevent clogging in the system.

The experiment was performed with four variables, the feed and carry pressure, and the feed and carry flow rate. The other four variables, feed head speed (16 ips), feed head height (7 in.), spray nozzle, and material (PVC), were all kept constant. The sintering was simulated using a gas torch. The experiments were conducted on a qualitative basis because the clogging problem hindered all efforts to produce a consistent powder layer, while a simulated roller experiment was also conducted for comparison.

The data gathered from the experiment was interesting. When the first layer of powder was applied and sintered, it formed several holes in the surface, through which the work plate was visible. When the second layer of powder was applied, the holes were gone. After sintering only a few holes allowed the work plate to be exposed, and there were also a few valleys in the surface. When compared with the simulated roller work pieces, the holes were shallower, and fewer. The layer thickness ranged from 12 to 16 mills for a single layer and 20 to 28 mills for two layers with a variance of two or three mills on each work piece.

An error was made during the experiments that lead to the most interesting discovery. One layer of powder was applied with all of the flow reduction valves off, thus letting a large amount of powder flow out of the spray nozzle. Unlike the previous experiments, a large amount of powder was floating in the air around the spray head after the application. When parts fabricated this way were measured, they were consistently 24 to 26 mills thick, regardless of the variable settings, and only had a thickness variance of one mill.

Clogging was observed in the system each time the powder flow was cut off. The clog was easily removed by closing all of the flow reduction valves and letting the clog blow out. However, the clogging phenomena has not been eliminated from the process.

Analysis

Several important characteristics can be seen in the experiment and the theoretical model of the process. The model shows that a charged particle will tend to settle in the center of a valley of like charged particles, thereby filling the valley. The experiment also demonstrated that a charged particle will tend to the holes or valleys in a work surface.

The layers applied with the flow reduction valves off are very informative. It appears that the powder settles on the work surface and builds layer thickness until enough charge is built up that it starts repelling additional charged powder particles which are attempting to come to rest upon the work surface. This process provides excellent filling of the hills and valleys because this thickness is constant for a given material and charge.

The clogging phenomena and the inability to produce layers that are as thin as are needed for selective laser sintering (5 mills) leads to the need for a redesigned system. The current system provides information about how the electrostatic process works, but it is not capable of the accurate and reliable performance needed in the selective laser sintering process.

Suggestions

There are several ways that the system may be redesigned to control the thickness and eliminate the clogging problem. The current pneumatic system may be modified to allow the powder to be forced into the carry flow by the natural vacuum of the flow over the powder orifice. This may be accomplished by either using a mechanical piston to keep the powder level at a constant height in a feed tube, or by building a dosing chamber that only allows the desired amount of powder into it, and uses the natural vacuum to empty itself.

A better method may be to not use pneumatics at all. This system, called the sieve feed system, consists of a powder container, a charged wire mesh, and squeegee on a linear actuator. The powder container drops a desired amount of powder onto the mesh using gravity. The squeegee then pushes the powder across the wire mesh while forcing it through. This system is more versatile because it can work in a vacuum, and it does not have the problem of pneumatic clogging.

The control of the layer thickness poses a different problem. Leaving the system with an open loop control process does not provide enough control to keep a rigid layer thickness. The thickness could be controlled using a feed back measuring system, particle charge control, or a simple mechanical scraper or roller. The feed back measuring system would be a process of applying and sintering a layer, finding and filling problem spots with the measuring system, and then applying a new layer and sintering it. The particle charge control would use the particle layer repulsion phenomena to control the thickness of the layers. The scraper is the simplest method, it simply removes an applied excess of powder to keep a constant layer thickness.

Conclusions

The electrostatic powder application system helped the particles find and fill valleys in the work piece, and helped with powder packing. The current system is not able to provide thin enough layers and suffers from problems with clogging and therefore, it needs to be redesigned. The best redesign would consist of the sieve feed system with a simple roller or scraper for thickness control.

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