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High Velocity Pulsed Plasma Thermal Spray

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The quality and durability of coatings produced by many thermal spray techniques could be improved by increasing the velocity with which coating particles impact the substrate. Additionally, better control of the chemical and thermal environment seen by the particles during flight is crucial to the quality of the coating. A high velocity thermal spray device is under development through a Ballistic Missile Defense Organization Small Business Innovation Research (SBIR) project, which provides significantly higher impact velocity for accelerated particles than is currently available with existing thermal spray devices. This device utilizes a pulsed plasma as the accelerative medium for powders introduced into the barrel. Recent experiments using a particle imaging diagnostic system showed that the device can accelerate stainless steel and WC-Co powders to velocities ranging from 1500 to 2200 m/s. These high velocities are accomplished without the use of combustible gases and without the need of a vacuum chamber, while maintaining an inert atmosphere for the particles during acceleration. The high velocities corresponded well to modeling predictions, and these same models suggest that velocities as high as 3000 m/s or higher are possible.

Keywords equipment, high velocity, pulsed plasma process, spray systems diagnostics

1. Introduction

Thermal spraying[1,2] is the process of applying coatings of high performance materials, such as metals, alloys, ceramics, cermets, and carbides, onto more easily worked and cheaper base materials. The purpose of the coating is to provide enhanced surface properties to the cheaper bulk material of which the part is made. Because of its ability to deposit virtually any material (and many combinations of materials), thermal spray has a wide and growing range of applications.

Coatings are a pervasive technology, permeating throughout all of industry and high technology applications. Coating technology is an enhancing technology that improves products and reduces cost. In many applications, coatings make it possible to achieve ends that cannot be achieved in any other known way or in any way that is affordable.

The quality of coatings produced by many thermal spray techniques could be improved by, among other things, increasing the velocity with which coating particles impact the coated surface and by controlling the chemical and thermal environment experienced by the particles during acceleration and flight.

A new and innovative approach to thermal plasma spraying called pulsed plasma spray (PPS) is described that dramatically increases coating particle velocities while simultaneously controlling the chemical and thermal environment of the particles. This process utilizes a repetitively pulsed plasma jet generated by a capillary arc discharge at high stagnation pressure (>100 MPa or 15,000 psi) and high temperature (>10,000 K). These plasma jets can be used in a variety of ways to melt and accelerate coating materials. Described here is a specific implementation that is reminiscent of traditional detonation spray techniques but with potential performance advantages that go far beyond the capabilities of either detonation gun, high velocity oxygen fuel spraying (HVOF), or traditional plasma spraying.

The existing state of the art currently peaks out at roughly 1200 m/s and requires the often undesirable use of combustible gases. The PPS process described here can produce controlled particle velocities that are a factor of 2 to 3 above this value, i.e., into the 2000 to 4000 m/s range. This is achieved with independent control of the chemical and thermal environment seen by the powder particles.

In this paper, the basic approach to using pulsed plasma discharges will be described, followed by a discussion of a heuristic conceptual model, and concluding with a description of a specific practical implementation called the reverse shock tube configuration.[3] The latter has been experimentally tested with some interesting results applicable to the cold spray[4] approach.

2. Pulsed Plasma Spray—A New Approach

For many years, the use of pulsed plasma discharges has been studied by UTRON personnel (UTRON, Inc., Manassas, VA) and others, for applications in rocket thrusters,[5] wind tunnels,[6,7] and to accelerate macroparticles (i.e., projectiles of mass >1 g) to hypervelocity.[8,9,10] These capillary discharges readily produce conditions of high pressure, high temperature, and high-velocity gas (plasma) flow that are exactly what is desired for heating and accelerating powder particles. The trick is how to harness this incredible source of heat and pressure to do useful work. In single-shot mode, as is the case for electrothermal guns, these discharges can be designed to melt anything and to accelerate small powder particles to velocities easily exceeding 10 km/s. Even macroparticles have been accelerated to above 7 km/s in the electric light gas gun,[11] an advanced variant of pulsed electric discharges. But such single shot devices typically use disposable ablative plastic liners, making them of no utility for a commercially viable thermal spray device. The main issue then is how to make this technology repetitive so that use can be made of the high pressure, high temperature, and high momentum flux that can be generated by a capillary discharge.

The basic PPS concept is shown schematically in Fig. 1. Its

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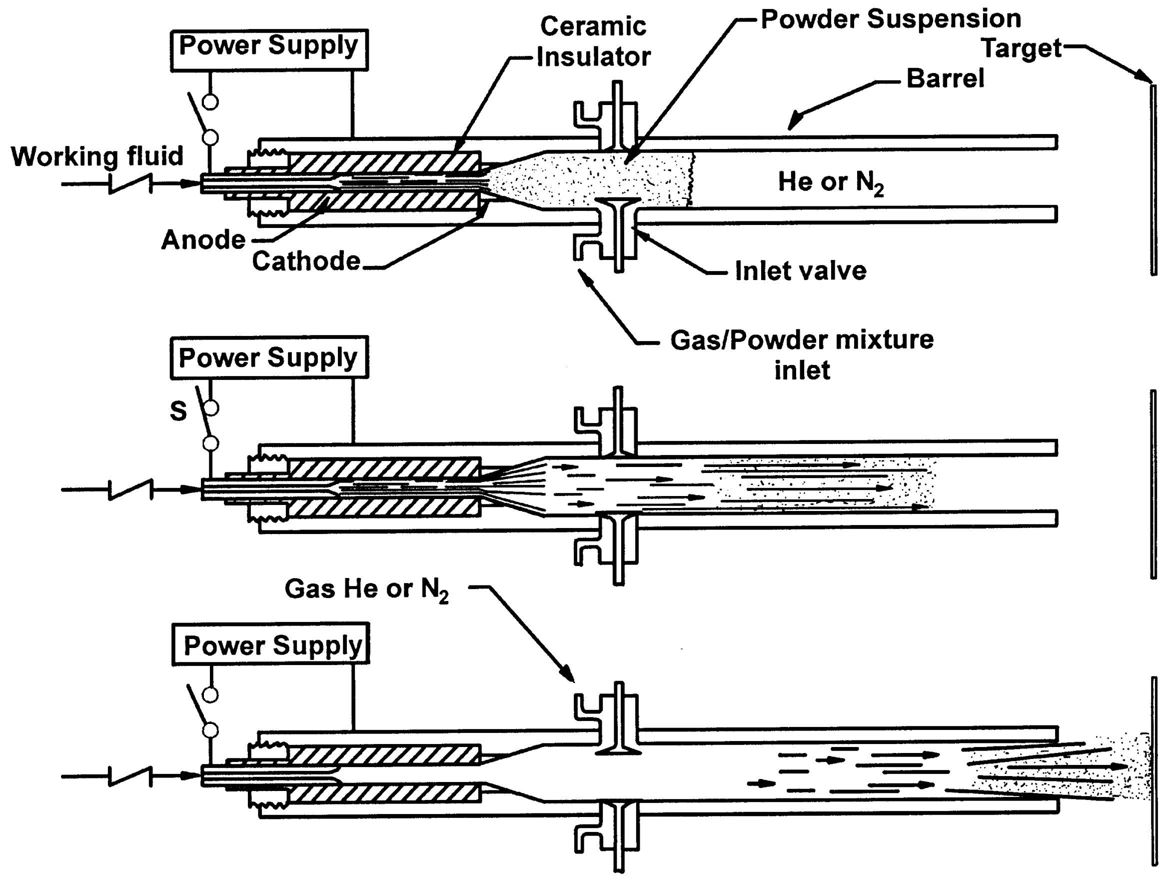

Fig. 1 Operational sequence of a PPS shot

operation is somewhat analogous to that of a detonation gun but with some significant differences. In a detonation gun,[12] oxygen and fuel (typically acetylene) are mixed with a uniformly dispersed fine powder that is cyclically injected into a 1 m long shotgunlike barrel (1 in. diameter) at a pressure of 1 atm. A spark at the breech end ignites the mixture and a supersonic detonation wave propagates down the barrel. The wave is so fast that the entire mixture is ignited before the rising gas pressure can be relieved through the muzzle (which occurs at sonic speed). The entire barrel rapidly rises to about 1 MPa (~150 psi) and about 3500 K, heating the dispersed powder. The powder is then accelerated and expelled along with the hot gas. Gas velocity in the detonation gun reaches about 2 to 3 km/s depending on the exact gas mixture used.

In the PPS concept, the chemical energy input is replaced by a very short duration but high-power electrical-arc discharge in a small insulating capillary that heats a working fluid or gas to 100 MPa (15,000 psi) or more and 1 eV (11,600 K) or more. The heated plasma rapidly expands down the barrel, picking up and accelerating powder particles placed in the barrel just at the exit of the capillary, as shown in Fig. 1. The device can operate in a vacuum or at atmospheric pressure. The working fluid can be introduced to the capillary in the form of solids, liquids, or gases, as discussed in Section 4. When switch S (Fig. 1) is closed, the electrical energy stored in the capacitor bank is transferred to the capillary in the form of a hot arc discharge. The time scale for this discharge is very short, typically tens to hundreds of microseconds.

The hot, high density high pressure plasma exits through the open end of the capillary. Expansion of the plasma down the barrel cools the gas and accelerates it. Flow velocities of >20 km/s are readily obtained in this fashion in a vacuum,[9] with somewhat lower velocities achieved in air. The actual velocity is controlled by the specific geometry, the molecular weight, the specific heat ratio of the gas, and the background gas pressure. After the pulse, inert gas is once again admitted, flushing the system and preventing air from re-entering the barrel through the muzzle. The cycle then begins again. An inert gas shroud could be incorporated into the muzzle to help protect particles from interacting with air prior to impact on the substrate.

3. Background on Capillary Discharges

The capillary discharge has been used at energies from below 1 J to above 1 MJ at instantaneous power levels from 100 kW to 1 GW. Pressure levels from 10 to 10^4 atm have been achieved. This versatile device has a number of distinct advantages that make it ideal for generating the required gas flows, and it has been developed over the past decade for applications in defense, space, and energy. Capillary discharges find some specific applications for accelerating masses in the electrothermal gun,[8-10] for producing thrust in the pulsed electrothermal (PET) thruster,[5] and for generating high enthalpy flows for advanced wind-tunnel research.[6,7]

The basic capillary discharge device is illustrated by the left half of Fig. 1. It consists of a long, narrow discharge channel comprised of an insulating wall with electrodes at either end. One end, usually the cathode, is closed off to contain the pressure generated by the discharge. The anode end is formed by an annular electrode, sometimes with an inner diameter that may be smaller than the capillary (forming a throat), through which the discharge plasma flows.

The capillary discharge chamber typically uses an ablative plastic liner to provide the working fluid, but repetitive systems can be (and have been) designed which use nonablative ceramic walls and injection of a working fluid.[5] The capillary is then driven with a short electrical pulse, anywhere from tens of microseconds to 2 to 3 ms in length, usually from a capacitive pulse-forming network (PFN). The length and diameter of the capillary are chosen so as to create the desired temperature of the gas in the capillary (for the given pressure), which is heated and ionized by the discharge, forming a plasma. This temperature, combined with the capillary geometry, creates an electrical resistance, which is matched to the impedance of the PFN. As is well known, under matched conditions, the stored energy is efficiently transferred from the PFN to the discharge load in a single pulse. Typically, the discharge resistance is designed to be high, 0.1 to 1 ohms. Since the parasitic resistance of the transmission circuit and the PFN is small (a few milliohms), most of the PFN energy is transferred to the discharge. Transfer efficiencies of >99% are not uncommon.

The working mass can also be introduced either as a liquid or a gas.[13] This was previously demonstrated experimentally in both the PET thruster program[5] and in the electrothermal wind tunnel program[6,7] in the early 1990s.

In electrothermal (ET) guns, substantial amounts of energy are introduced into the capillary discharge. Up to several megajoules (MJ) have been fired this way. In these tests, pressures reach 3000 to 6000 atm, and temperatures can exceed 2 eV in some cases. The physics of these highly ablative capillary discharges has been studied in great detail by Tidman et al.,[14,15] where the basic equations describing the operation of ablative liner capillary discharges are derived.

4. The Basic Pulsed Plasma Jet Sprayer

Acceleration of a single-coating powder particle is determined by solving the drag equation:[12]

$$\frac{dv_p}{dt} = \frac{3}{4}\frac{C_d}{d_p}\left(\frac{\rho_g}{\rho_p}\right)(v_g - v_p)^2$$

where v_p, ρ_p, and d are the particle velocity, density, and diameter, respectively; ρ_g and v_g are the gas density and velocity as determined by the fluid equations; and C_d is the drag coefficient, which is approximately 0.44 for most cases of interest here. This equation shows that for a given particle size and density, the determining factors are the velocity of the gas relative to the particle and the density of that gas. The higher the gas density and the higher the relative velocity, the stronger is the accelerating force on the particle. In essence, one of the goals of all thermal spray devices is to maximize this quantity.

The goal then is to identify a repetitively operating hardware configuration that maximizes the quantity $\rho_{gas}\,(v_{gas} - v_{powder})^2$, provides the appropriate thermal energy and heating time, and whose critical hardware components survive for commercially reasonable times. Since the capillary liner must be constructed of a high performance ceramic (which is operated in a completely nonablative mode), the main issue is how to introduce a working fluid into the capillary region in a repetitive manner that provides sufficient mass to accelerate the powder without exceeding chamber and barrel temperature limits. It turns out that it is desirable to operate the capillary discharge at roughly 1 kbar and 1 eV (11,600 K) to achieve the desired performance.

Providing the working fluid by continuous liquid and gas injection is addressed in a separate program and reported in a separate paper.[16] It turns out that the best approach is supplying the mass in the form of a gas. Such an approach necessarily utilizes a ceramic insulator for the capillary liner, which must be operated in a completely nonablative mode in order to achieve the long lifetime and low cost operations required for commercial feasibility.

The first thing to consider is how much gas is required. A conservative estimate is that a mass of gas roughly 4 to 10 times the mass of powder to be accelerated per pulse will be required.

As an illustrative case, consider a nominal deposition rate of 1 kg/h at a pulse rate of 10 Hz. (There are no fundamental reasons why deposition rates a factor of 5 to 10 or more higher than this could not be achieved.) This implies a mass of about 30 mg of powder per pulse. This means that the gas mass in the capillary must conservatively be on the order of 300 mg in order to accelerate the powder. In order to keep the fill pressures at reasonable values, a capillary size of 1 to 2 cm diameter and a length of 10 to 20 cm was selected. As will be seen later, a 2 cm diameter by 20 cm long capillary filled to 30 atm with an Ar + 3He mixture contains 1000 mg of gas. This is more than sufficient and provides a large margin of error with which to work. After ohmic heating, this mass of gas will attain a pressure of 1 kbar (15,000 psi) at 1 eV (11,600 K). If less gas is placed in the capillary, the peak pressure must be reduced in order to keep the temperature from going too high and damaging the ceramic insulator. These parameters allow pulse lengths of hundreds of microseconds.

Since a ceramic insulator must be used for the capillary liner,[17,18] the thermal loads to the wall must be considered to determine at what temperatures the capillary discharge can be allowed to operate and for how long. The temperature rise of a surface subjected to a sudden heat flux, q, is given by $\Delta T = \alpha q t^{1/2}$, where $\alpha = 2/(\pi \rho c k)^{1/2}$, Δ is density, c is the specific heat, and k is thermal conductivity. This equation indicates that ablation can be avoided for a given heat flux, q, by keeping the pulse time sufficiently short. The so-called "grace period" is the time a surface can be exposed to a given thermal flux before ablation begins and is different for each material as determined by its α and vaporization temperature.

Figure 2 illustrates the time scales for representative heat-flux parameters for BN and SiC insulators. The curves without asterisks represent the case for a flat, radial temperature profile in the capillary, while the curves with asterisks represent the more realistic case in which a lower-temperature boundary layer forms at the wall, which can reduce the heat flux, q, to the wall by as much as a factor of 2 over the heat flux calculated from the core plasma temperature on the axis. The two curves with aster-

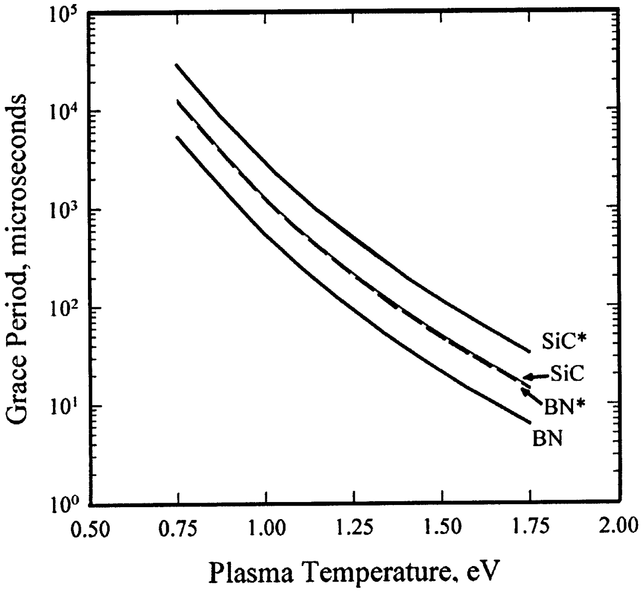

Fig. 2 Grace period for BN and SiC insulators. The two curves labeled with asterisks are for the case of a wall flux 33% lower due to boundary-temperature reduction effects.

isks indicate the increase in grace period for only a 33% drop in energy flux to the wall.

It is clear that, for advanced ceramics, the capillary discharge can be operated at temperatures in the 1 to 1.5 eV range for 100 to 1000 μs without ablating the ceramic insulator. The conservative assumption that temperature should be limited to 1 eV, and the capillary should not be exposed to this temperature for more than 200 to 300 μs was usually made in the code runs. Note that it is desirable to operate at as high a temperature as possible in order to maximize pressure for a given prefill density and to maximize the gas sound speed, which ultimately determines the powder particle speed.

5. The Burst Diaphragm Configuration—A Heuristic Conceptual Model

The only way to obtain sufficient gas mass is to mechanically confine the gas. Consider a thin (ideally zero mass) diaphragm placed across the capillary exit, as shown in Fig. 3. The capillary is then filled with an inert working gas, typically an argon/helium mixture, although any gas can be used. While the capillary is pressurizing, coating powder is puffed into the barrel just downstream of the diaphragm. Once the capillary is pressurized to a preset value, which turns out to be in the 10 to 30 atm range, the plasma discharge is initiated. The rapidly rising pressure of the discharge bursts the diaphragm and the hot gas flows down the barrel, heating and accelerating the powder particles as it goes. Peak pressure in the capillary reaches about 1 kbar, and the temperature reaches 1 eV (11,600 K) or so. The discharge is designed so that temperature does not go beyond the 1 to 1.5 eV range in order to prevent the capillary wall from ablating. The core plasma temperature can actually be allowed to go as much as 50 to 100% higher than this since a cooler boundary layer

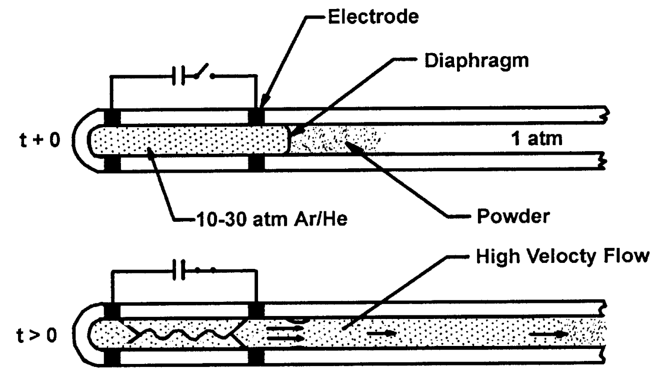

Fig. 3 A burst diaphragm configuration captures the essence of a capillary discharge sprayer using high density gas in a conceptually simple configuration.

forms at the wall, which reduces the energy flux relative to the core.

This is clearly an energetic event. The question, of course, is whether this approach can attain the desired performance levels with respect to the powder velocity. The performance capabilities of a pulsed-plasma jet sprayer with an integral burst diaphragm are now discussed.

6. Modeling

The numerical method used to simulate the sprayer is an algorithm developed in the 1970s specifically for the solution of time-dependent flow problems containing steep gradients and shocks. The method, called flux-corrected transport (FCT),[19,20] incorporates very general methods for accurately calculating the dynamics of fluid equations and then correcting the computed results to remove the numerical errors, which are a byproduct of conventional finite-difference numerical calculations.

FCT has been applied elsewhere to both viscid and inviscid flow and has been tested on many practical problems. The FCT algorithm is designed to efficiently solve the generalized continuity equation:

$$\frac{\partial f}{\partial t} + \nabla \cdot f\bar{v} = D$$

This general form is applied to the specific transport equations in a conservation form, which allows variation in the cross-sectional area of the tube:[15]

$$\frac{\partial}{\partial t}(\rho A) + \frac{\partial}{\partial x}(\rho u A) = \left(\frac{d\rho}{dt}\right)_{\text{ablation or injection}}$$

$$\frac{\partial}{\partial t}(\rho u A) + \frac{\partial}{\partial x}\{(\rho u^2 + p)A\} = p\frac{\partial A}{\partial x} - \frac{\lambda}{2d}\rho u^2 A$$

$$\frac{\partial}{\partial t}\left\{\left(\frac{1}{2}\rho u^2 + W\right)A\right\} + \frac{\partial}{\partial x}\left\{\left(\frac{1}{2}\rho u^2 + W + p\right)uA\right\} = -\pi d q_{\text{wall}} + (\text{ohmic heating})$$

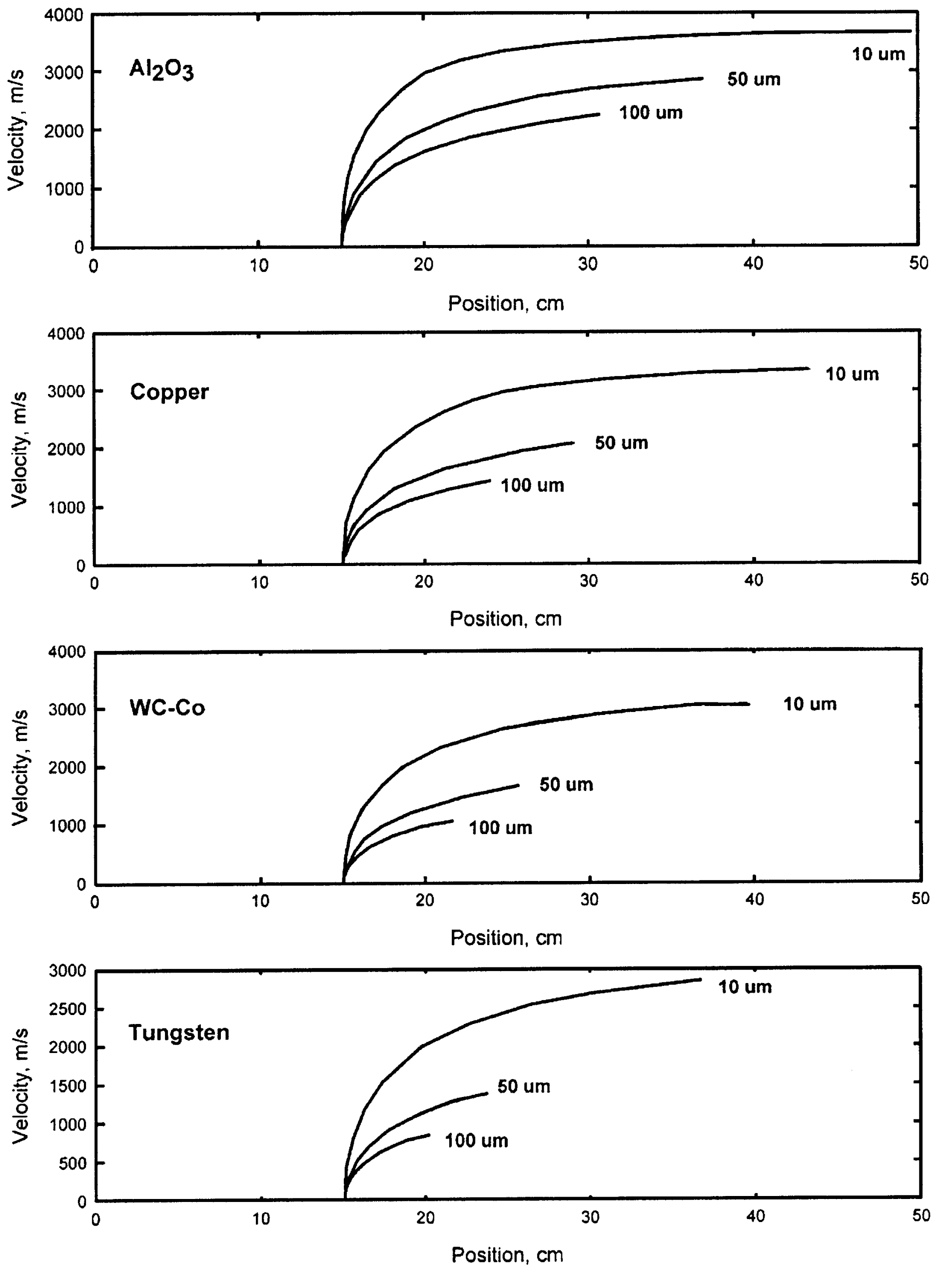

Fig. 4 Predicted performance for a burst diaphragm sprayer for 10μ (upper), 50μ (middle), and 100μ (lower) powders of Al_2O_3, Cu, WC-Co, and W powders, respectively

$$q_{\text{wall}} = \sigma (T^4 - T^4_{\text{wall}}) + 10^{-3} \frac{\gamma}{\gamma - 1} pu \, \Psi \left(\frac{T - T_{\text{wall}}}{T} \right)$$

where the second term in q_{wall} is due to radiation transport and turbulent convective-heat transport.[14] The equations are closed by an equation of state.

Initial code runs quickly indicated the need to operate in the 1 kbar range. Working backward yields the density required to obtain 1 kbar pressures at 1 eV. For the Ar/He mix, this turns out to correspond to a prefill pressure of about 30 atm. A prefill of 10 atm allows peak pressures of about 0.33 kbar, which is still substantially above existing thermal-spray devices.

Simulation results are now presented for the case of a capillary 2 cm in diameter and 10 cm long and a barrel 1 cm in diameter and 50 cm long. The capillary is filled with a 1 kbar plasma (Ar + 3He mix) at 10,000 K, which corresponds to an ohmic energy input of 5 kJ. The resulting powder-velocity time histories are shown in Fig. 4. For programming ease, the calculation is halted when the 10μ Al_2O_3 particle reached the barrel exit. (Future versions will upgrade this to allow all particles to reach the barrel exit.)

Note that the 10μ particles tend to come up to speed fairly quickly and then basically "coast" with the flow the rest of the way since the relative velocity has become rather small and, con-

Table 1 Energetics for 30 mg of Powder

	Al_2O_3	WC-Co
Energy to heat to *T* melt, J	66	15
Energy to melt, J	30	15
Total thermal energy required to melt, J	96	30
Kinetic energy at 2000 m/s, J	60	60

sequently, the accelerating drag. The larger particles will continue to accelerate inside the barrel and will actually attain roughly another 500 m/s in velocity. The barrel allows the larger particles to continue accelerating. This effect seems to indicate that with some optimization, relatively narrow velocity distributions could be achieved. The velocities of these larger particles are already greater than the velocities currently attained by only 10μ particles in existing thermal-spray devices. Note that if less He is used in the mix, e.g., Ar + He instead of Ar + 3He, then peak performance drops from a peak velocity of 3680 to 2930 m/s for the 10μ particles. This is obviously still far above present thermal-spray capability and uses a cheaper mix, so there is a lot of room to adjust the mix. Other gases can also be used. Since the energy is supplied electrically, there is freedom to choose the working fluid to optimize chemistry or other parameters of interest.

For this case, total capillary-gas mass was about 500 mg, indicating that at least 50 mg of powder, and probably 125 mg, could be accelerated without significantly affecting the projected performance. At 10 Hz, this corresponds to a 1.7 or 4.2 kg/h spray rate, respectively, for an average power of 50 kW.

Now consider some of the energetics. What energies are required to heat, melt, and accelerate powders to 2000 m/s? Table 1 presents the numbers for Al_2O_3 and WC-Co. In each case, a nominal 30 mg/pulse is assumed. For Al_2O_3, it can be seen that it takes only 66 J to bring the powder up to the melting temperature and an additional 30 J to actually melt it. The kinetic energy of the powder at 2000 m/s is 60 J. If the spray is designed to heat the powder just to melt temperature, the kinetic energy of impact can supply the additional heat of fusion required to actually melt the particle. At 2000 m/s, there is plenty of kinetic energy available to do this. The crossover point is at about 1500 m/s at which the kinetic energy of impact just equals the heat of fusion. At the higher velocities attainable with PPS, the temperature of the particle can actually be significantly below the melt temperature and still melt on impact. This latter case has been called impact fusion,[21] and there is evidence of it already occurring in some experiments. The PPS will allow very extensive testing of this exciting concept.

Note that 10 to 20 kJ of energy is being dissipated in the capillary via ohmic heating. The total amount of energy required to heat and accelerate the Al_2O_3 powder is on the order of 140 to 150 J, only 1.5% of the total available. Such numbers are consistent with detonation gun and plasma spray even though they deliver considerably less performance. At these pulse energies and pulse rates, average powers of 100 to 200 kW can be expected. It is relatively simple to scale to larger size and energy and increase the deposition rate accordingly. Such is not the case for conventional combustible-gas sprayers where safety becomes more and more of an issue at higher pressures and gas flow rates.

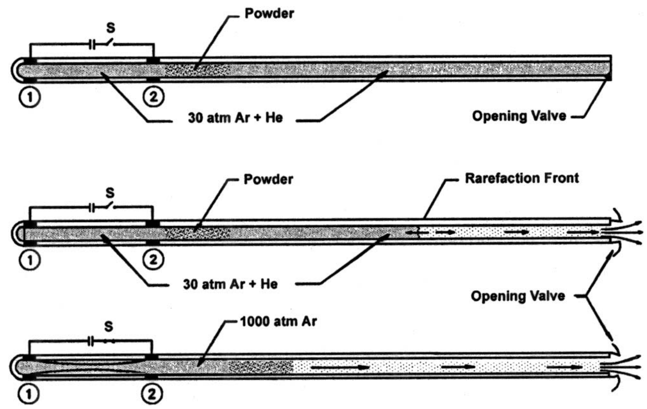

Fig. 5 Reverse shock tube configuration. Capillary discharge fires upon arrival of rarefaction wave at electrode 2. Other variations of this configuration are possible and have been considered for advanced operations.

To make most efficient use of the gas in the capillary, the powder needs to be initially placed right at the exit immediately downstream of the second electrode. Placing the powder to the left of the electrode actually drops performance measurably, precipitously in fact, if the powder is placed at the center of the capillary.

The projected performance of a pulsed-plasma jet sprayer with an integral burst diaphragm is quite spectacular. However, such a system is not practical due to the diaphragm itself, so a way to emulate the configuration is needed.

7. The Reverse Shock Tube Configuration—A Practical Implementation

The reverse shock tube approach provides an elegant and practical solution to approximating the burst diaphragm configuration. It does so by making use of the physics of shock tubes.[22]

In this configuration, shown in Fig. 5, the goal is achieved in a somewhat backward manner. Initially, the entire barrel is filled with 10 to 30 atm of inert gas, using a sealing shutter at the muzzle. On receipt of a trigger signal, the muzzle shutter quickly opens and gas starts venting from the barrel. This causes a rarefaction wave to propagate back up the barrel. The rarefaction front travels at the local sound speed of the gas. By the time the rarefaction wave reaches the capillary region (at electrode 2), less than half the original gas remains in the barrel, and the gas that does remain is accelerating toward the muzzle. It is at this time that the capillary discharge is triggered. Capillary pressure quickly rises to about 1000 atm and expands down the barrel, snowplowing and accelerating the residual barrel gases and the powder toward the muzzle. The gas remaining in the barrel does tend to reduce the peak velocity that could otherwise be obtained with an empty barrel, but the effect is modest, reducing peak powder velocity by only about 20 to 25%. After this effect is taken into account, this approach still produces velocities in excess of 2000 m/s for 10μ sized particles and velocities well above

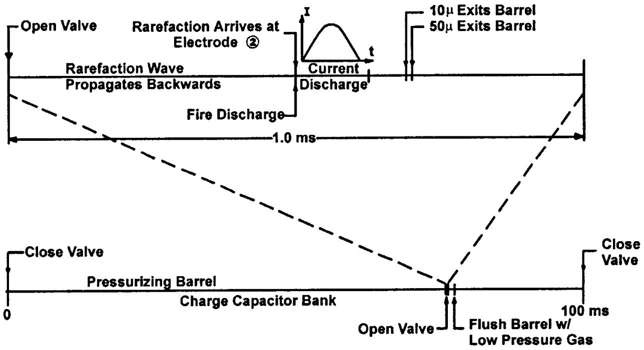

Fig. 6 Nominal timeline for reverse shock tube configuration shows sequence of events for a 10 Hz rep-rate. The main spray activity occurs in the small (–1 ms) window between pressurizing the barrel and flushing the barrel.

Table 2 Nominal Parameters for the Reverse Shock Tube Sprayer Configuration

System Parameter	Value
Barrel length	50-70 cm
Barrel/capillary identification	2 cm
Capillary length	10-20 cm
Gas density	0.01575 g/cm^3
Gas mass in capillary	1000 mg
Peak powder velocity	3000 m/s
Deposition rate	1-5 kg/h
Powder mass per pulse	30-125 mg
Pulse rate	4-10 pps
Fill pressure	10-30 atm
Peak pressure	−1000 atm
Peak temperature	−1 eV
Energy per pulse	10-20 kJ
Average power at 10 Hz	100-200 kW

1000 m/s for 50μ sized particles, a dramatic improvement over existing technology.

The configuration appears to be ideal for performing cold spray[4] due to the fact that the powder particles tend to be confined to a region ahead of the expanding jet in which the gas is highly compressed and in which the temperature can be reduced.

An operational timeline is shown in Fig. 6, and system parameters are shown in Table 2. Note that the barrel inner diameter is similar to the detonation gun, but that barrel length is only 50 to 70% that of the detonation gun. An inner diameter of 2 cm was chosen to allow a more direct comparison with the performance of the detonation gun and because this is a commercially attractive size due to the spot size it creates on the substrate.

The velocity performance for this simulation is shown in Fig. 7, where the velocity attained by Al_2O_3, Cu, WC-Co, and W powders of various sizes is plotted. Such performance should be compared to the detonation gun, which can achieve 1200 m/s only for the 10μ particles and only about 400 to 500 m/s for 50μ particles.

This performance is nearly as good as that obtained from the burst diaphragm configuration discussed previously. The difference, of course, is a result of having a higher density of gas in the barrel against which the plasma jet must work. This is alleviated to some extent by the fact that this gas is not stationary but moves to the right with an ever-increasing speed.

8. Experimental Hardware

System: The spray system is shown schematically in Fig. 8. The capillary discharge is contained in the plasma jet chamber on the left. Followed in turn by the powder feeder, the barrel, and the fast muzzle valve. Compare this figure with the illustration in Fig. 5.

Pulsed Plasma Source: The discharge chamber consists of a steel jacket heat shrunk around a ceramic capillary with sufficient prestress to allow operation up to about 1 kbar. A water-cooled outer jacket allows repetitive operation.

Barrel: The plasma chamber connects to a barrel approximately 0.7 m long. It consists of a tantalum liner inside a steel outer jacket. The barrel does not have provision for water cooling at present but can be modified to include it later. Water-cooling will be required for commercial operation.

Gas System: Gas is admitted to the barrel and capillary at several locations along the length of the barrel, as shown, including through the rear electrode to the capillary itself, as suggested by Fig. 1.

Powder Feeder: Powder is fed into the barrel at one location at the beginning of the barrel section a few centimeters downstream from the capillary exit.

Ignition: Breakdown of the high-pressure gas is accomplished with a fast-rising high-voltage pulse.

Muzzle Valve: A fast opening/sealing valve is located at the muzzle. It currently opens in 1 to 2 ms.

Control System and Diagnostics: The entire spray system is controlled by a computerized system connected to the device through a fiber optic cable. The computer controls all valves, timing, triggers, etc. required for the operation of the device. One piezoelectric pressure transducer is presently located just downstream of the capillary exit and powder feeder to provide pressure time histories.

Power Supply: The power supply presently consists of a small bank of capacitors located in a room immediately adjacent to the spray booth. The capacitors are charged by a high-voltage charging supply. The presently available charging supply limits operation to about 1 Hz.

9. Experimental Results

During the course of this SBIR Phase II program, UTRON rented a particle-velocity diagnostic system (a LaserStrobe, Control Vision, Inc., Idaho Falls, ID) from Drexel University (Philadelphia, PA). This system uses one or more pulsed nitrogen lasers operating at a 337 nm wavelength to illuminate particles traveling in a thermal spray jet. Reflected laser light is captured by a charge coupled device (CCD) camera. By setting the camera shutter to an appropriate setting (a few microseconds), "twin" images of particles appear in a single video frame because the images caused by the two lasers, although not simultaneous, occur near enough in time to each other to both be captured in a single video frame. These individual frames can be digitized using a video frame-grabber and

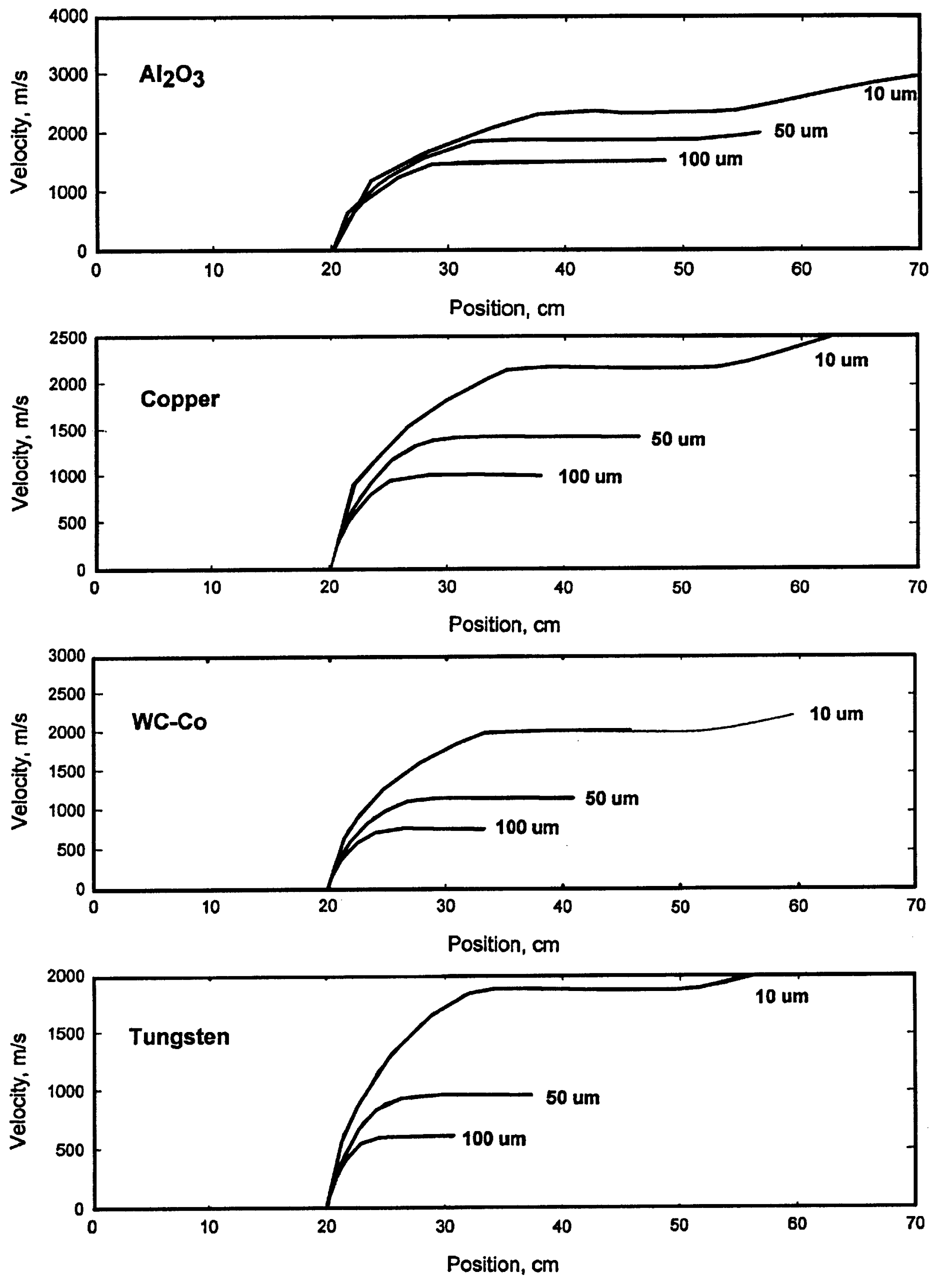

Fig. 7 Predicted performance for the reverse shock tube configuration for 20 kJ discharges in an Ar/He mix at 450 psi prefill

analyzed to measure the distance that a given particle has moved between the two laser pulses. Velocity is calculated based on this distance of travel and by knowing the time between laser pulses.

The PPS shots were performed using this dual laser process, and the results are plotted in Fig. 9. Data were taken at various times within individual plasma shots, and this explains the fairly large variance in these results. Those data recorded during the peak period of plasma exiting the barrel showed the highest velocity, while those data taken slightly before or after the peak showed correspondingly lower velocities. For the low energy (12 kJ) shots with the PPS device, velocities of the WC-Co particles ranged from 1084 to 1721 m/s. For the higher energy shots (18 kJ), the velocities ranged from 1548 to 2233 m/s.

Analysis of the microstructures of stainless steel coatings supports the high-velocity and low-temperature impact fusion model. The particle velocities attained with the UTRON, Inc. Pulsed High Acceleration Spray Technique (PHAST) technology is in the 2000 m/s range, and the temperature of the particles is less than the melting temperature of the alloy. At this velocity and temperature, the stainless-steel powder particles impact the target with sufficient kinetic energy to cause plastic deformation and bonding. This phenomenon is referred to as impact fusion.[4,21] A micrograph showing the cross section of a representative stainless steel PHAST coating is presented in Fig. 10. The powder particles, which were originally spherical as a result of the powder atomization process, are now deformed and more

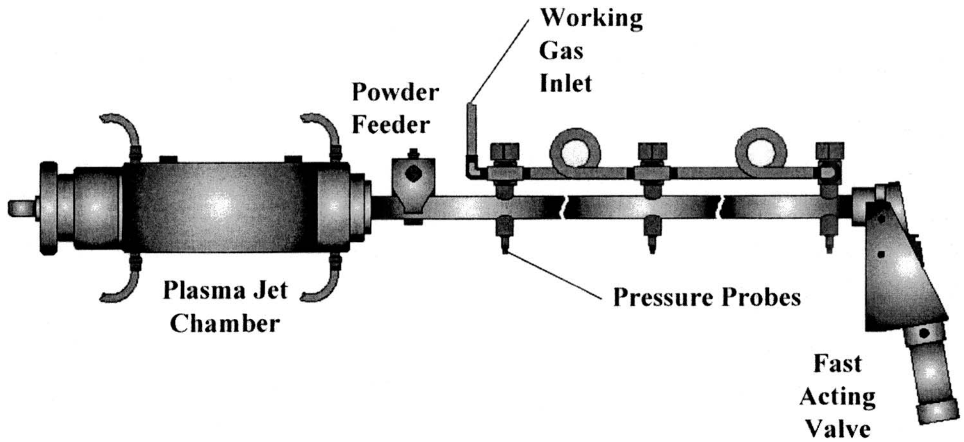

Fig. 8 The PPS device as constructed for Phase II testing

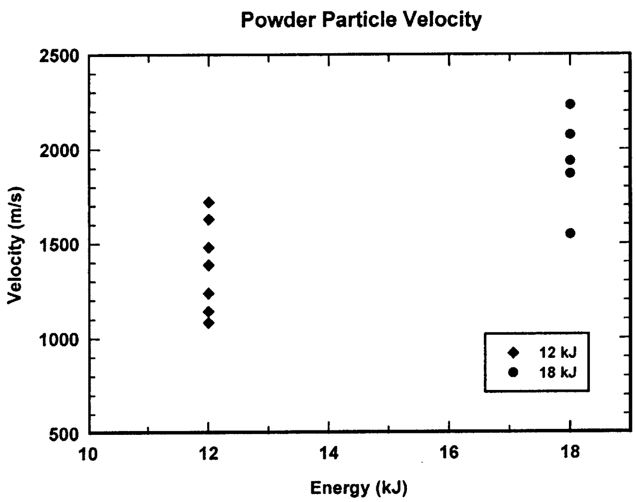

Fig. 9 Powder velocity of WC-Co particles accelerated by the UTRON PPS device

Fig. 10 Micrograph of a PPS stainless-steel coating

oval in shape. The high particle velocity results in sufficient kinetic energy to deform and tightly pack the atomized particles leaving relatively little porosity in the interstices between the particles in the coating. The observed microstructures also indicate the temperature of the particles at impact is below the melting temperature of stainless steel. At higher temperatures, a lamellar microstructure would be expected.

Figure 11 shows the microhardness as a function of distance from the coating surface for three stainless-steel samples. The harder coating region below the surface is due to a cold working or peening-type effect resulting from the solid powder particles, below their melting temperature, impacting the previously deposited material during the coating process.

The following PHAST advantages are expected to result in improved coating quality compared to slower thermal-spray methods.

- Low porosity due to the plastic deformation of particles produced by high velocity impacts.
- High hardness resulting from a microstructure similar to that of cold-worked alloys.
- The composition and phase of the feed powder is maintained in the coating due to the relatively low temperature of the process.
- Little or no oxidation of the deposited material because the atmosphere in the barrel is inert. In addition, the relatively low temperature and fast time of flight of the particles between the barrel and substrate reduces the opportunity for oxidation.

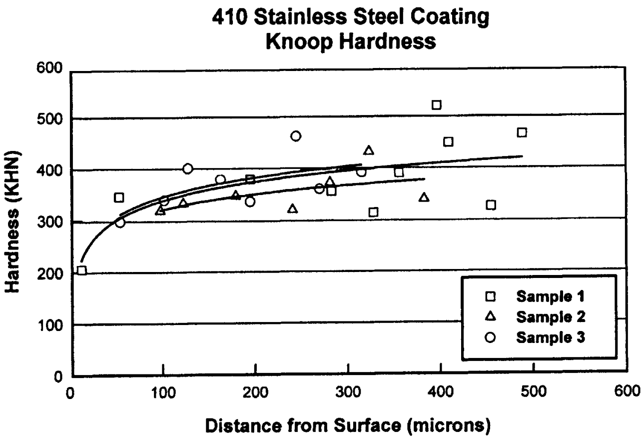

Fig. 11 The microhardness of stainless steel coatings is lower at the surface.

10. Summary

A new thermal-spray technology is described that uses the power of pulsed capillary discharges to heat and accelerate injected powder particles. Since all energy input is via electrical discharge heating, the approach can use virtually any gas, in particular, inert gases. The pulsed energy input results in pressures and densities far higher than conventional thermal-spray techniques, with momentum fluxes a factor of 100 to 1000 larger.

The technique has been experimentally demonstrated at a 1 Hz pulse rate with powder velocities above 2000 m/s. Pulse rates of 10 to 20 Hz are ultimately expected. Velocities as high as 3000 to 4000 m/s may be possible if desired.

The novel method of establishing the initial shot conditions leads to an almost ideal configuration for cold spray in which powder particles can be accelerated to velocities two to three times higher than current cold-spray techniques can produce.

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A patent[23] for this spray technology was issued during preparation of this manuscript.

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