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Technical Note

The Effect of Torch Hardware on Particle Temperature and Particle Velocity Distributions in the Powder Flame Spray Process

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Powder flame spray is a flexible, straightforward process. Particulate feed stock is heated and accelerated using an oxy-fuel flame. Liquid feed stock droplets impact the substrate, deform, and solidify to form a coating. Like other spray processes, coating microstructure and properties are directly related to particle velocity and temperature at the time of impact. Many controllable process inputs affect particle temperature and particle velocity. Data, from a series of designed experiments, exploring these factors and quantifying their significance are reviewed. These data show that multiple process inputs, especially torch hardware, can significantly affect particle temperature and velocity distributions in the powder flame spray process.

Keywords diagnostics and control, powder flame spray, torch hardware

1. Introduction

Process reliability and consistency is extremely important, especially in thermal-sprayed coatings. In many cases, sprayed coatings are critical to system performance: if the coating fails, the system fails (Ref 1). Many critical choices affecting the reliability and consistency of the coating process are made during process development. The data presented here show that process inputs such as total flow (TF) of combustible gases, oxy-fuel ratio (OFR), and standoff distance (SD) can be directly related to particle temperature (T_p) and particle velocity (V_p). It is well known that T_p and V_p can be chosen to provide specific coating microstructure and properties. Increasingly measured T_p and V_p data are being used for process development and monitoring. Often these measurements are made at a single small point in the spray plume. Interestingly, the data presented here show that, in the case of the powder flame spray process, a particular T_p, V_p condition measured along the plume centerline can be reached by many different process settings. Furthermore, the data show that how a particular centerline T_p, V_p condition is reached can be as important as what centerline T_p, V_p condition is reached. These details can significantly affect data interpretation, process development choices, and process monitoring approaches.

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2. Experimental Procedure

Multiple designed experiments were conducted to characterize the effect of process gas flows and hardware choice on the T_p, V_p space accessible to a Sulzer-Metco 6P powder flame spray torch (Ref 2). These data were used to create linear models for each hardware set, allowing prediction of T_p and V_p in terms of process gas flows. These equations were used to drive the 6P torch to the same T_p, V_p condition using different hardware sets and gas flow conditions. These experiments have been reported in detail previously and are only summarized here; for complete details see Ref 2 and 3.

A 6P Powder Flame Spray Torch spraying a 34 µm Al_2O_3-13%TiO_2 powder (Saint Gobain-Norton, Worcester, MA) mounted on a Stäubli RX60 6-axis robotic arm (Staubli International, Pfäffikon, Switzerland) was characterized using a DPV-2000 (Tecnar Automation, Quebec, Canada). The DPV-2000 measurement volume was always located at the plume centerline unless otherwise noted. Process gas flows were set using calibrated Alicat Scientific (Alicat Scientific, Tucson, AZ) MC Series laminar mass flow controllers. A Praxair 1260 hopper (Praxair Inc, Danbury, CT) was used for all powder feed. Powder feed rate was measured by placing the hopper on an AND GP-100KS scale (AnD A&D Weighing, San Jose, CA) and measuring weight change versus time.

The 6P "M," "K," and "D" nozzles (Fig. 1) as well as the flame cooling, gun cooling, and pinch air caps (Fig. 2) were characterized using an augmented central composite experimental design with 28 points. TF of combustible gas (oxygen + acetylene) was varied from 35.4 to 44.8 slpm. OFR was varied from 1.5 to 2.5. SD was varied from 14.5 to 19.1 cm. Air flow and powder feed rate were fixed at 165.2 slpm and 10 g/min, respectively. Powder gas flow rate was fixed at 4.7 slpm.

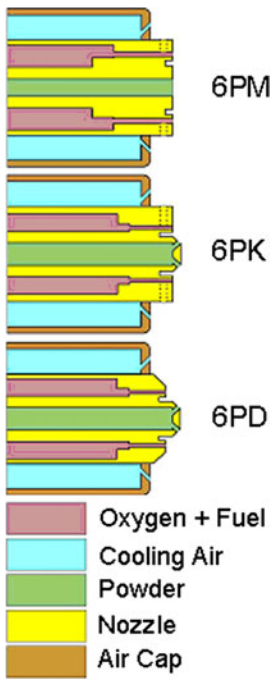

Fig. 1 Schematic showing differences between "M," "K," and "D" nozzles

Scientific deposition efficiency (DE) was measured by spraying a grit blasted 2 by 2 in. stainless steel coupon, and the ratio of the amount of material deposited on the substrate to the amount of material sprayed was calculated while the torch was directed at the substrate The amount of material deposited was determined by measuring the weight change of the substrate. The amount of material sprayed was calculated from the measured powder feed rate and the time on part as determined from the robot path and speed.

Cross-sectional maps of T_p, V_p distributions within the spray plume were prepared by using the DPV-2000 to measure T_p and V_p every 5 mm within ±15 mm of the torch centerline at SDs of 13.97 cm (5.5 in.), 16.51 cm (6.5 in.), and 19.05 cm (7.5 in.).

3. Results and Discussion

Data from each designed experiment was fit to a liner model using Minitab® (Minitab® Inc., State College, PA) describing the response of each nozzle/air cap combination (Ref 2). These equations, given in Ref 2, were used to map the T_p, V_p space accessible to each nozzle/air cap combination. Figure 3 shows the operating space available to the 6P "M," "K," and "D" nozzles with the gun cooling air cap. The "M" nozzle produced the lowest T_p and V_p values. The "D" nozzle produced the highest T_p and V_p values.

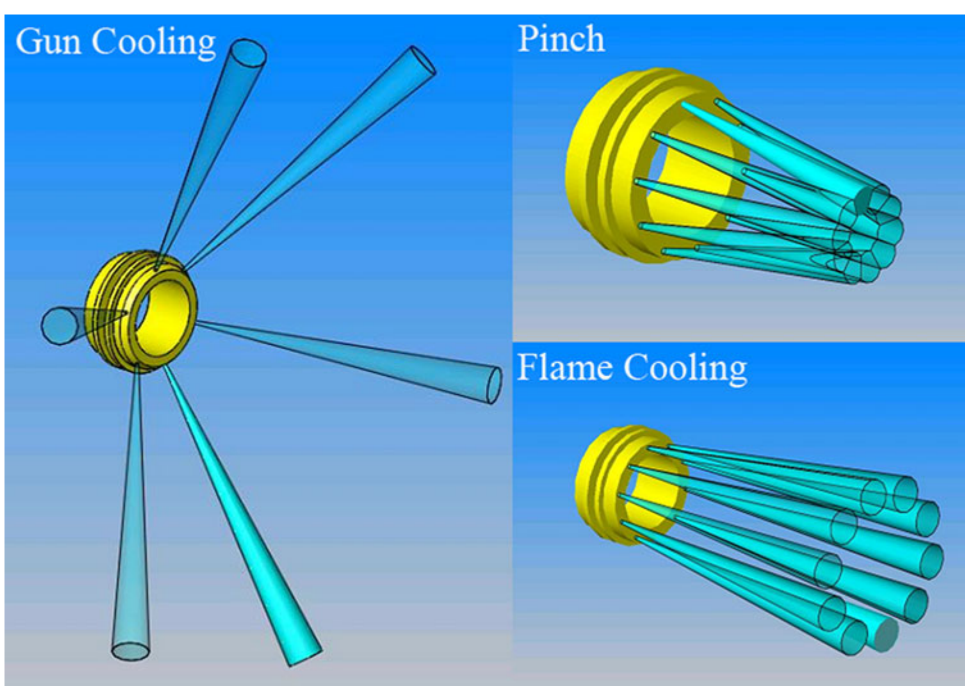

Fig. 2 Schematic showing differences between "gun cooling," "flame cooling," and "pinch" air caps

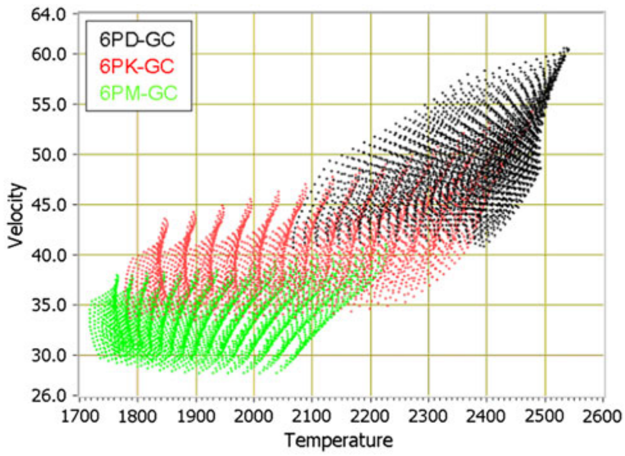

Fig. 3 T_p, V_p space available to the 6P "M," "K," and "D" nozzles with the gun cooling air cap

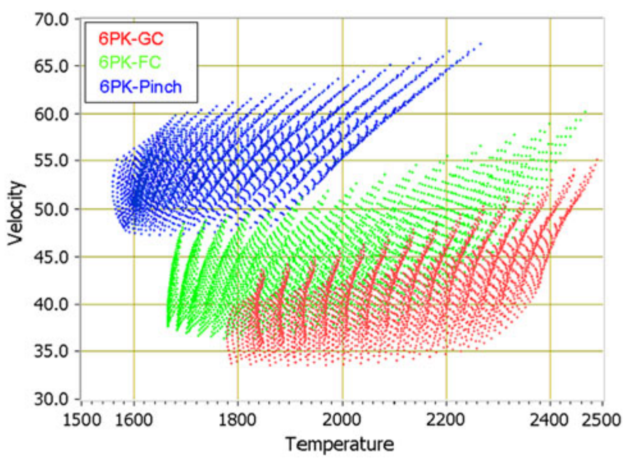

Fig. 4 T_p, V_p space available to the 6P-"K" torch with the gun cooling, flame cooling, and pinch air caps

The "K" nozzle produced T_p and V_p values that were in between those of the "M" and "D" nozzles. These differences are largely due to the differences in end geometry of the powder feed tube in each nozzle (Fig. 1). The "M" nozzle delivers the powder to the center of the flame where it does not interact as strongly with the flame jets. The "D" nozzle directs powder into the flame jets resulting in the highest T_p and V_p values. The "K" nozzle also directs powder into the flame jets, but does so less aggressively than the "D" nozzle. Thus, choice of nozzle significantly affected the accessible T_p, V_p space.

The T_p, V_p space accessible to the "K" nozzle using gun cooling, flame cooling, and pinch air caps is shown in Fig. 4. As expected, the gun cooling air cap produced the highest T_p and the lowest V_p values because it minimized the interaction between the cooling air and the particulate loaded flame. Conversely, the pinch air cap strongly directed cooling air into the flame and produced the highest V_p and the lowest T_p values. The flame cooling air cap also directed air into the flame but not as strongly as the pinch air cap, and as a result, the flame cooling air cap produced T_p and V_p values between those of the gun cooling and pinch air caps.

Choice of nozzle (Fig. 3) allows torch performance to move along a diagonal in T_p, V_p space that is orthogonal to the diagonal that is created by changing air caps (Fig. 4). This means that by choosing the appropriate hardware combination (nozzle/air cap), it is possible to access a very large region of T_p, V_p space. In fact, almost the entire T_p, V_p space between 1500 to 2500 °C and 30 to 70 m/s can be accessed. Interestingly, in much of the accessible T_p, V_p space, different nozzles/operating condition combinations can be used to reach the same centerline T_p, V_p condition.

It is reasonable to expect that operating at the same nominal point in T_p, V_p space (centerline T_p, V_p) should result in a similar spray plume. In order to test this hypothesis, T_p, V_p data were used to choose a single point in T_p, V_p space that could be accessed using three different hardware/operating condition combinations. DE was then measured using different hardware/operating condition combinations. The T_p, V_p condition chosen was 2100 °C, 45 m/s. This choice was arbitrary and was driven primarily by the observation that most nozzle/air cap combinations tested could access this region. The DPV-2000 was used to verify that each torch was operating at the intended centerline T_p, V_p condition before making DE measurements. Table 1 shows the DE data from this experiment. It clearly demonstrates that the same DE cannot be reached simply by producing the same centerline T_p, V_p.

Table 1 Deposition efficiency data taken at the same T_p, V_p (2100 °C, 45 m/s) condition using three different torches (6PK-FC, 6PK-GC, and 6PDGC)

Hardware	TF, scfh	OFR	SD, in.	Target T_p	Target V_p	Actual T_p	Actual V_p	DE, %
K-FC	79.0	1.92	5.64	2100	45.0	2108.32	45.15	64.02
D-GC	95.0	2.00	7.35	2100	45.0	2100.93	44.88	36.83
K-GC	95.0	1.80	5.50	2100	45.0	2109.10	44.54	75.20

The observation of different DEs at the same nominal T_p, V_p condition can be explained by different T_p, V_p distributions in the spray plume. The DPV-2000 was used to create plume cross-sections showing T_p, V_p distributions within the spray plume (Fig. 5, 6). Different nozzle and air cap combinations result in different T_p, V_p distributions within the spray plume. Changing the T_p, V_p distribution within the plume presumably results in different particle melting behavior and different DEs. The gun cooling air cap yields a broader distribution of particle temperatures and lower particle velocities than the flame cooling air cap, regardless of SD. This behavior is a result of directing the gun cooling air into the spray plume more or less aggressively.

The data in Table 1 show that the gun cooling air cap produces the highest DE. This is the same hardware set that produced the most uniform T_p, V_p distribution in the spray plume. This experiment illustrates the importance of

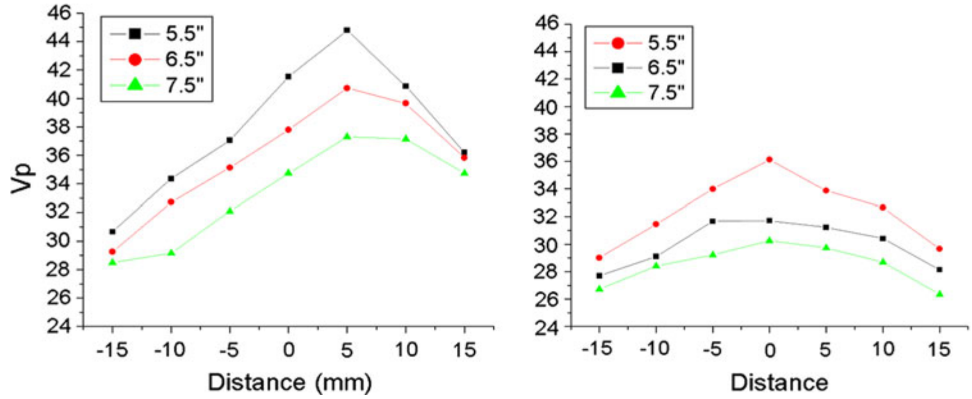

Fig. 5 Effect of flame cooling (left) and gun cooling (right) air caps on 6P-K particle velocity in m/s (*Y*-axis) across the plume (*X*-axis) and with SD (symbols)

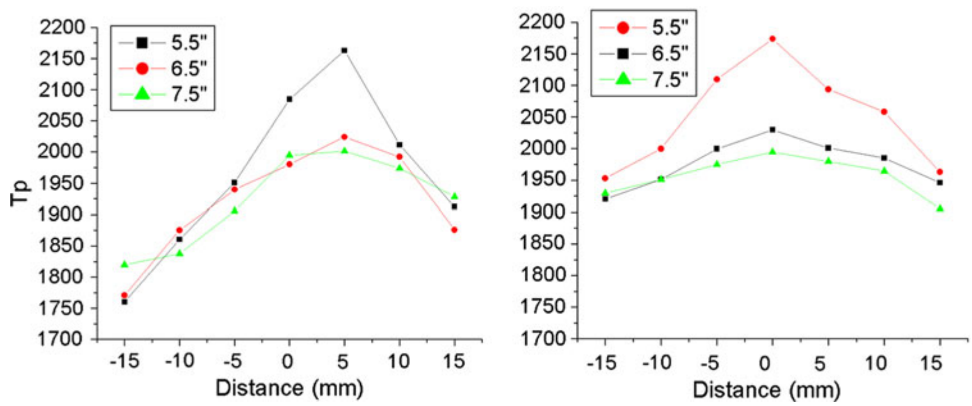

Fig. 6 Effect of flame cooling (left) and gun cooling (right) air caps on 6P-K particle temperature in °C (*Y*-axis) across the plume (*X*-axis) and with SD (symbols)

hardware choice and measurement approach when using centerline T_p, V_p data for process development or monitoring. Choosing a hardware set that provides a uniform T_p, V_p distribution instead of one that produces a broad T_p, V_p distribution should simplify data collection because small changes in position between the spray plume centerline and the sensor are unlikely to result in large changes in measured T_p or V_p. In a long-term process monitoring situation, choosing hardware that produces a uniform T_p, V_p distribution should reduce measurement noise and allow for easier identification of real process drift.

4. Conclusions

Complete separation of T_p, V_p conditions and particle distributions within the spray plume is not possible. However, considerable changes in T_p, V_p distributions at a single nominal (centerline) T_p, V_p condition can be made by selecting different torch hardware. The above-mentioned findings highlight the need to consider T_p, V_p distributions when choosing torch hardware and T_p, V_p measurement approaches. In these situations, hardware sets that produce more uniform T_p, V_p distributions are likely to produce a more easily characterized coating process. Thus, how a particular T_p, V_p is reached should be considered in addition to what T_p, V_p is reached.

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