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Effect of Torch Hardware on Oxy-Acetylene Powder Flame Spray Performance

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ABSTRACT

The effect of hardware on operating parameters and the resultant coating are qualitatively known; however, the quantitative effects have not been well defined. This study quantitatively characterizes particle temperature and velocity for the Sulzer-Metco 6P oxy-acetylene torch with 3 different nozzles and 3 air caps and also, the Alamo PG550 then relates those data to particle diagnostics, deposition efficiency and coating microstructure. Both torches were evaluated using statistically designed experiments where the process inputs of oxy-fuel ratio, total combustible gas flow, and standoff distance were varied. Both torches can access similar regions of particle temperature - particle velocity space. Increasing total combustible gas flow increased particle velocity with little effect on particle temperature. Increasing oxy-fuel ratio decreased particle temperature with little effect on particle velocity. Higher particle velocity and particle temperature conditions yielded denser, less porous coatings. Flame cooling air caps increase the particle speed while decreasing particle temperature. Nozzles which inject powder directly into the flame jets significantly increase particle temperature as compared to nozzles which do not. Deposition efficiency is shown to not only be affected by particle temperature and particle velocity where hotter and faster usually increase efficiency, but is also dependent on the distribution of particles within the plume.

Introduction

The process of thermal spraying is very complex with many interrelated variables. In the case of oxy-acetylene flame spraying of powders, the process variables include fuel type, oxygen-to-fuel ratio, total flow of combustible gas (sum of oxygen and fuel gas flow rates), stand off distance from torch to substrate, powder feed rate, powder gas flow rate, air flow, raster speed, particle size, and others. In addition, there are numerous hardware configurations that may be selected. There is often a choice of air caps that direct the air toward the flame or away from the flame. Similarly, gun nozzles can also have different geometries; e.g., powder is delivered to the center of the flame or powder is directed toward the flame jets. How these process variables and hardware choices affect torch performance has not been thoroughly investigated in a quantitative manner.

Process mapping has become a popular means to characterize torch performance as particle diagnostic techniques have become available [1-6,8]. Process maps relating process variables to particle temperature and velocity within the plume and subsequent deposition provide valuable information for the production community as well as researchers. To date, most process mapping has focused on either plasma, high velocity oxy-fuel, or wire arc spraying[2,5] with only limited work on powder flame spraying[7,8].

Deposition efficiency (DE) is an integrated measure of the economy and performance of a thermal spray process. Scientific DE is the ratio of the amount of material deposited on a substrate to the total amount of material sprayed while the torch is directed at the substrate. All process parameters contribute to deposition efficiency. For this reason, DE is a useful tool for monitoring overall stability of a thermal spray process. In general, DE is expected to increase as particle temperature, T_p, and particle velocity, V_p, increase. Hotter, faster particles have a greater chance of adhering to the substrate and contributing to the coating.

This study focuses on two very different torches: Alamo PG-550 (Alamo Supply Company, Inc., Houston, TX) and the Sulzer-Metco 6P (Sulzer-Metco, Winterthur, Switzerland). The primary purposes were first, to experimentally determine the operating spaces of the torches and second, to develop an understanding of the relationship between powder flame spray process parameters including hardware choice, and the resulting coating.

Experimental Procedure

The PG-550 torch with an “M” nozzle was selected to this study. The “M” nozzle was designed for spraying metal powders but was found to perform well with the alumina-titania powder used in this work The 6P torch was evaluated using 3 different nozzles: M,K, D and three different air caps: Gun Cooling air cap (GC), Flame Cooling (FC) and Pinch air caps. The 6P-M nozzle is similar to the PG-550 M nozzle while the 6P-K and 6P-D nozzles both have a shower head like geometry with the D nozzle delivering powder farther downstream of the flame jets and having a different number of jets. Diagrams and pictures of each nozzle are shown in Figure 1. The air caps for the 6P are shown in Figure 2.

All experiments in this study were conducted by spraying an alumina-13%titania powder (Saint-Gobain-Norton, Worcester, MA). This powder is a fused and crushed ceramic with a mean particle size of 17 μm. A Praxair Model 1260 (Praxair, Danbury, CT) powder hopper with an automatic tamping system was used to feed.

A design of experiments approach, specifically, augmented central composite design(CCD), was used to characterize the effect of process variables on torch performance, specifically, T_p and V_p, measured using the DPV-2000 (Tecnar Inc., Montreal Canada) with no substrate present. The process variables examined were total flow of combustible gasses (TF), oxy-fuel ratio (OFR), and standoff distance (SD).

Scientific Deposition efficiency (DE) was used as an integrated measure of the economy and performance. It is the ratio of the amount of material deposited on a substrate to the total amount of material sprayed while the torch is directed at the aluminum substrate.

Sectioned coatings on substrates were mounted in epoxy using a vacuum impregnation process, then polished using standard metallographic techniques. Optical and scanning electron microscopy were used to examine the coating microstructure.

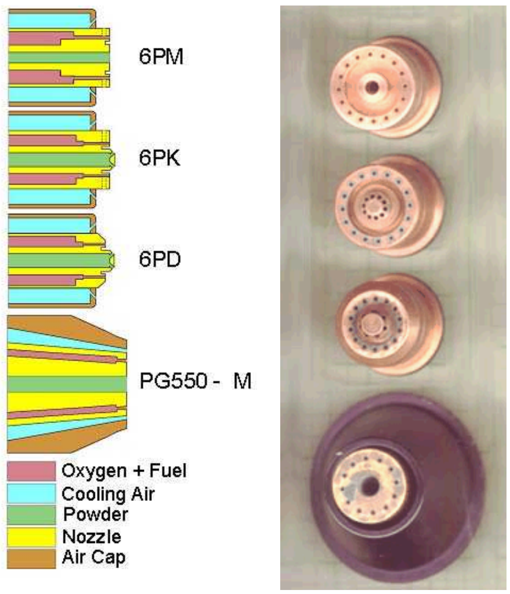

Figure 1 6P Torch with M, K, and D Nozzles and the Alamo PG-550 M

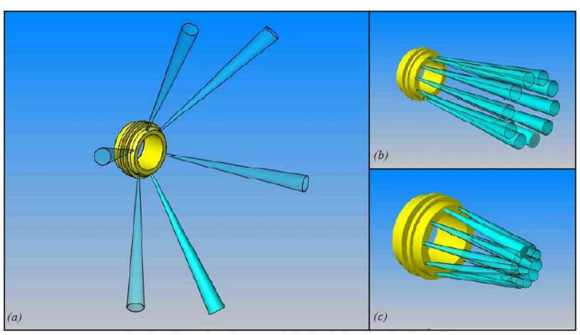

Figure 2 6P torch air caps :(a) Gun Cooling (b) Flame Cooling and (c) Pinch

Results and Discussion

An augmented CCD with 28 points was used to characterize the effects of TF, OFR, and SD on Tp, Vp, DE, and microstructure. This experimental design was used to characterize the 6P-M, 6P-K, and 6P-D nozzles with the gun cooling air cap, the 6P-K nozzle with the flame cooling air cap, the 6P-K nozzle with the pinch air cap, and to characterize the PG-550 nozzle. TF was varied from 75-95 SCFH, OFR: 1.5 to 2.5, SD: 5.5”- 7.5”, air flow and PFR were fixed at 350 SCFH and 10 g/min, respectively. Powder gas flow rate was fixed at 10 SCFH.

The first experiments compared 6P torch with 3 different nozzles and GC air cap with the PG-550. The OFR had the greatest effect on Tp for all hardware combinations while TF and SD had minimal influence. Oxy-Fuel Ratio has a strong effect on flame temperature. As the OFR of the oxy-acetylene flame was increased from 1.5, the flame temperature decreases. As the flame temperature decreases, the average particle temperature also decreases. It is noted that as stand off distance increases, T_p decreases. The differences in powder feed for each nozzle yield mean particle temperatures from approximately 1900 ºC to over 2500ºC. Figure 3 shows typical main effects plots for the for all hardware sets.

Examination of the V_p data shows that mean V_p tends to decrease with increasing OFR and SD but increases substantially with TF. This makes sense because TF is a measure of the total gas flow in the process. As the total gas flow is increased, the gas velocity must also increase. As the gas velocity increases, particle velocity increases assuming the particles stay in the flow field. These data also show that average V_p decreases slightly as standoff distance increases which is expected for any projectile. Data for the 6P-M-GC set are shown in Figure 4 and are typical trends for the other configurations.

As expected, higher T_p and V_p created denser, more adherent .coatings as shown by the microstructures and higher deposition efficiencies.

Using multiple linear regression, mathematical equations that describe the response of each torch / hardware combination were created. These equations were then used to generate a set of T_p, V_p conditions or operating space that are accessible to each torch. Figure 5 shows the envelope of operating space available to the 6P with M, K, and D nozzles and the gun cooling air cap and the PG-550. The 6P-M-GC produced the lowest T_p - V_p operating space while 6P-D-GC produced the highest T_p - V_p. The PG-550 covered a much larger area of T_p-V_p space overlapping the regions of both the 6P-K-GC and 6P-D-GC nozzles but not reaching higher T_p. These differences are largely due to the differences in the geometry of the powder feed tube in each nozzle (Figure 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 hottest portion of the flame jets resulting in the highest T_p and V_p. The K nozzle also directs powder into the flame jets, but closer to the nozzle face. The PG-550 exhibits a wider operating space due to the open geometry of the nozzle.

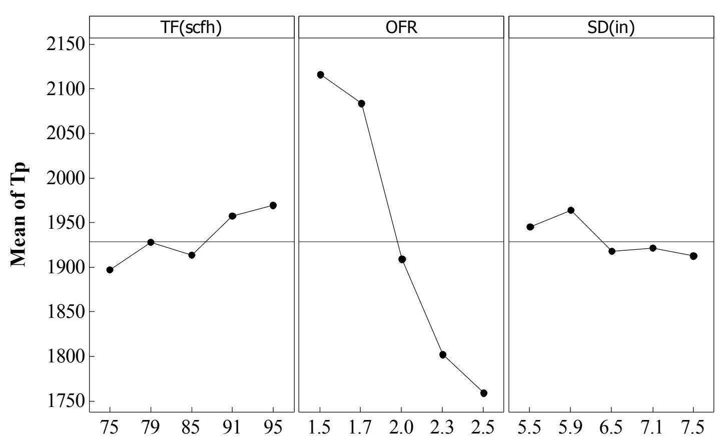

Figure 3 Effect of torch parameters on Mean Particle Temperature for 6P-M-GC Torch

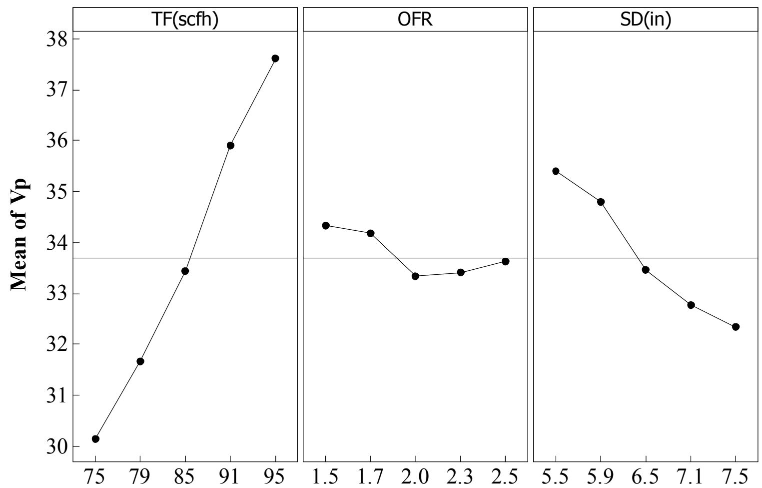

Figure 4 Effect of torch parameters on mean particle velocity for 6P-M-GC Torch

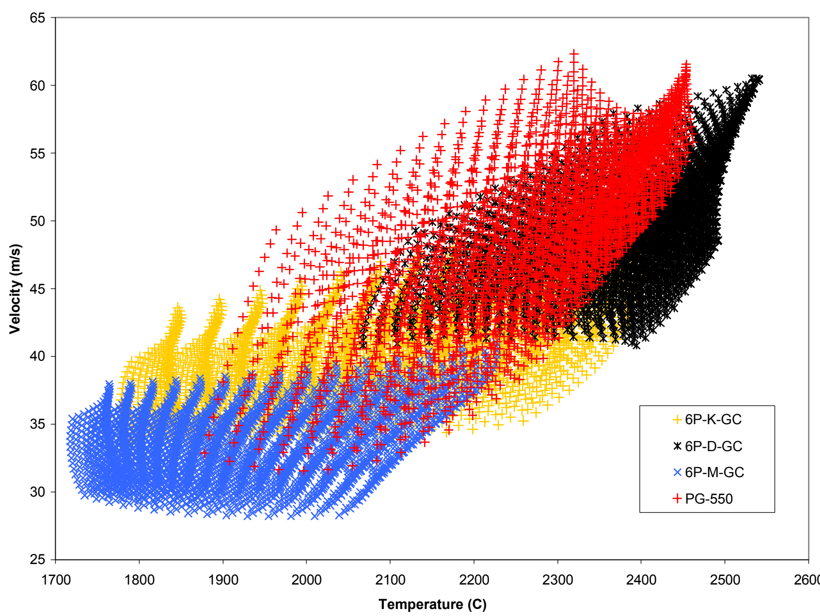

Figure 5 Operating space for 6P-M-GC, 6P-K-GC, 6P-D-GC, and PG-550 torches

The effect of TF, OFR, and SD on the 6P-K torch with the Gun Cooling (GC), Flame Cooling (FC), and Pinch Cooling (PC) air caps was investigated using the augmented CCD. For each air cap, the effect of TF, OFR, and SD was similar to the effects described in the previous section. T_p was greatly affected by OFR and less affected by SD and TF. V_p was most affected by TF and by SD and OFR to a lesser extent. The Pinch Cooling cap produced lower average particle temperatures and higher average particle velocities while the Gun Cooling cap produced the highest temperatures and lowest velocities. This is due to the differences in the geometry of the air caps.

Again, using a multiple linear regression model, the operating space in terms of T_p and V_p was determined for each air cap. Only the K nozzle was used in this study. As expected, the gun cooling air cap produced the highest T_p and lowest V_p because it minimized the interaction of the cooling air with the flame. The pinch air cap strongly directed the cooling air into the flame and produced the highest V_p and lowest T_p. The flame cooling air cap also directed air into the flame but not as strongly as the pinch air cap, as a result, the flame cooling air cap produced T_p and V_p values intermediate to the gun cooling and pinch air caps. Figure 6 shows the operating space available to the 6P-K with the GC, FC, and PC air caps.

Interestingly, the choice of nozzle (Figure 6) 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 (Figure 5). 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 1500-2500 °C and 30 - 70 m/s can be accessed using the 6P torch.

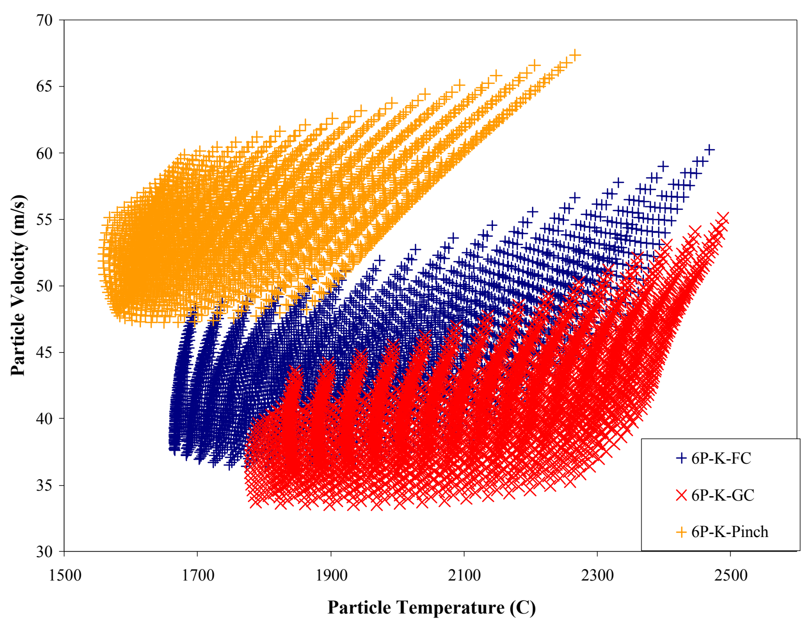

Figure 6 Effect of Air Cap on 6P-K nozzle operating space.

As part of the process mapping effort, the relationship between T_p, V_p, and DE was investigated. It is well known that T_p and V_p, at the time of impact, affect the deformation and adhesion behavior of the particles which affects DE. As shown earlier, OFR, TF and SD strongly affect T_p and V_p. Deposition efficiency measurements were made using the torches at different operating conditions. As expected, higher DE's were observed at the conditions that were known to produce higher T_p and V_p.

In much of the accessible T_p and V_p space, different hardware and/or operating conditions can be used to reach the same T_p, V_p condition. One might expect that any torch operating at the same point in T_p, V_p space should exhibit similar DE's. To test this hypothesis, T_p, V_p data (Figures 5 and 6) were used to select a single point that could be accessed using different hardware and operating conditions. Deposition efficiency was measured at that point using three different torch configurations and operating conditions. The T_p, V_p condition chosen was 2100°C, 45m/s located at the torch centerline and it was reached using 6P-K-GC, 6P-K-FC, and 6P-D-GC hardware. The DPV-2000 was used to verify that each torch configuration was operating at the intended centerline T_p and V_p before making the DE measurements. For these three hardware sets the DE varied from approximately 37% to 75% (Table 1). Analysis of coating microstructures confirmed these DE results. This demonstrates that the same DE cannot be reached simply by producing the same T_p and V_p. Even though the selected Tp was in the vicinity of the powder melting point, the choice of hardware strongly affects DE because of how heat is transferred to the particles.

Table 1 Deposition efficiency (DE) using three different torch hardware configurations

Torch Hardware	**T_p (°C)**	**V_p (m/s)**	**TF (SCFH)**	**OFR**	**SD (in)**	**DE (%)**
6P-K-FC	2108	45.2	79	1.92	5.6	64.0
6P-D-GC	2101	44.9	95	2.00	7.4	36.8
6P-K-GC	2109	44.5	95	1.80	5.5	75.2

The observation of different DE's at the same nominal centerline T_p, V_p condition can be explained by different particle temperature and particle velocity distributions in the spray plume. The DPV-2000 only measures T_p and V_p within a small volume of the plume, in this case, that volume was located at the plume centerline. Different nozzle and air cap combinations result in different T_p and V_p distributions within the entire plume which were evaluated using plume cross sections [8]. Because of this distribution of T_p and V_p, a range of particle melting behavior will occur in each plume. Some particles will be completely melted as expected. Other particles will melt fully and then solidify before impact, while some will not melt completely. These particles behave very differently upon impact even though the plumes have the same centerline conditions. These experiments highlight the need to understand not only the effect of process inputs (TF, OFR, SD) on the centerline conditions, but also to understand the behavior of the entire plume. Plume cross sections that map the spatial variation in T_p and V_p are necessary for full quantitative characterization of the powder flame spray process.

Conclusions

Sulzer Metco 6P oxy-acetylene torch with 3 different nozzles and 3 air caps and also, the Alamo PG-550 were found to cover the same general area in particle temperature - particle velocity space. Increasing the OFR greatly decreases T_p and has little effect on V_p. Increases in TF increases V_p but does not have much effect on T_p.

Torch hardware was shown to have a major effect on particle diagnostics, microstructure, and deposition efficiency. Air caps which direct cooling air to toward the flame have a major effect by increasing V_p and decreasing T_p. Air caps that primarily cool the gun do not affect particle characteristics as much as the nozzle geometry. Nozzles which inject powder directly into the flame jets significantly increase particle temperature.

Deposition efficiency varied greatly with different hardware sets and operating conditions which had similar Tp, Vp. This was shown to be dependent on the distribution of particles within the plume.

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