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Effect of Torch Hardware and Operating Parameters on Oxy-Acetylene Powder Flame Spray Heat Flux

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Abstract

The effect of torch hardware, operating parameters, and powder type on substrate surface heat flux was quantitatively investigated using calorimeters. The Sulzer-Metco 6P oxy-acetylene torch with two nozzles and two air caps and the Alamo PG-550 torch were studied using designed experiments to show the effects of total combustible gas flow, oxy-fuel ratio, air flow, and standoff distance on surface heat flux. Air caps which directed cooling air toward the flame produced lower heat flux than air caps providing gun cooling. For the 6P torch, nozzle geometry did not have a significant effect on heat flux. With low air flow rates, both torches exhibited similar heat fluxes. At high air flows, the surface heat flux of the PG-550 was larger than those for the 6P.

Introduction

Thermal spray coating performance depends on how a coating is deposited, which is a very complex process with many interrelated variables. These variables include not only process variables, but also hardware. How these process variables and hardware choices affect torch performance is qualitatively understood, but it has not been thoroughly investigated in a quantitative manner.

One common method to determine heat flux during the thermal spray coating process is to use two or more thermocouples embedded a calorimeter separated by a specified distance (Figure 1).

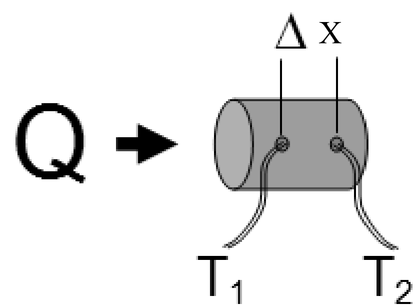


Figure 1: Schematic of calorimeter showing thermocouples embedded in a mild steel plug.

The temperature difference between the thermocouples is then used to calculate the heat flux using:

$$Q = kA(dT/dX)$$

where: Q is the heat flux, k is the thermal conductivity of the calorimeter, A is the cross sectional area of the calorimeter, and dT/dX is the temperature gradient in the calorimeter. The procedure to determine Q begins by moving the calorimeter in front of the torch, which is set at specified parameters for a given time period. Temperature data are collected using the two thermocouples, then the calorimeter is removed from the flame and air cooled to room temperature. Usually, the effect of the torch both with and without powder is determined. One-or multi-dimensional heat flow models are used to indirectly determine the surface temperature and surface heat flux from the temperature data as the coating builds. During deposition, the heat transfer coefficient includes both the effects of the spray process and the effect of impacting particles. In addition, there are radiation and convection heat losses. Researchers have examined heat flux during plasma spraying [1] and high velocity oxy-fuel spraying [2] by embedding thermocouples into the substrate. For oxy-acetylene flame spraying, Deng et al [3] developed a neural network based model of heat flux at different stand off distances. The surface heat flux in all cases decreased as the distance between spray gun and substrate increased.

Little research has been published on the effect of process variables and hardware choice in powder flame spraying [4]. Thus, the goal of this work is to quantitatively characterize the effect of hardware choices and process parameters on surface heat flux for powder flame spraying.

Experimental Procedure

Two different torches were examined: Sulzer-Metco 6P (Sulzer-Metco, Winterthur, Switzerland) and Alamo PG-550 (Alamo Supply Company, Inc., Houston, TX). To further show the effect of hardware differences, the 6P torch was configured with two nozzles (K, D) and two air caps (Gun Cooling and Flame Cooling) as shown in Figures 2 and 3. Both the 6P-K and 6P-D nozzles 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. The two 6P air caps direct the gun cooling air differently as it exits the torch. The gun cooling (GC) air cap directs the exiting air 60° away from the flame along the axis of the torch, while the flame cooling (FC) air cap directs the air 5° away from the flame. Powder is fed to the center of the flame in the PG-550 torch using an "M" nozzle and gun cooling is directed parallel to the flame (Figure 2

The powder flame spray torch was controlled using a gas control system built at Sandia National Laboratories. This system provides mass flow control of all the process gasses and is driven by custom LABVIEW™ 7 software (National Instruments Inc., Austin, TX) written at Sandia National Laboratories. A Praxair Model 1260 (Praxair, Danbury, CT) powder hopper with an automatic tamping system was used. In addition, the software controlled a robot to manipulate the calorimeter and executed an augmented central composite designed experiment automatically. The torch was set to the desired conditions, and then the calorimeter was placed within the flame at the desired standoff distance for a specified time. The calorimeter was then removed from the flame and cooled with an air knife until the internal thermocouples reached room temperature. This process was repeated for each condition of the design.

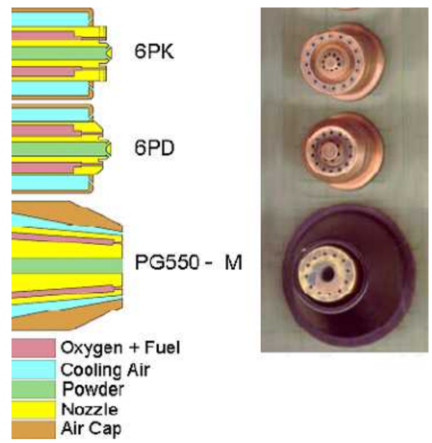
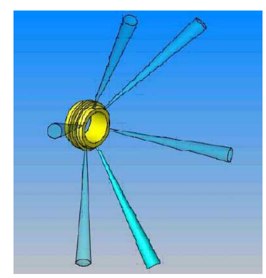
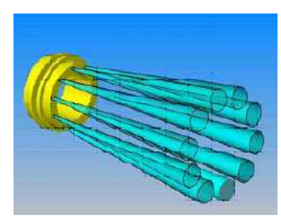


Figure 2: Torch configurations for Sulzer-Metco 6P K and D nozzles and Alamo PG550 "M"



(a) Gun Cooling Air Cap



(b) Flame Cooling Air Cap

Figure 3: Air cap configurations for Sulzer-Metco 6P torch

Plain carbon steel button calorimeters (Model TCS-K-12-10370, Midtherm Corp., Huntsville, AL) were used to determine torch heat flux (Figure 4). This button-type calorimeter which is 12.5 mm in diameter contains two Type K thermocouples separated by 0.42 mm and is surrounded by a layer of ceramic insulator approximately 8.0 mm thick to minimize lateral heat transfer. The collected temperature data were then converted to heat fluxes using SODDIT (Sandia One Dimensional Direct and Inverse Thermal code, Sandia National Laboratory, Albuquerque, NM, 1985).

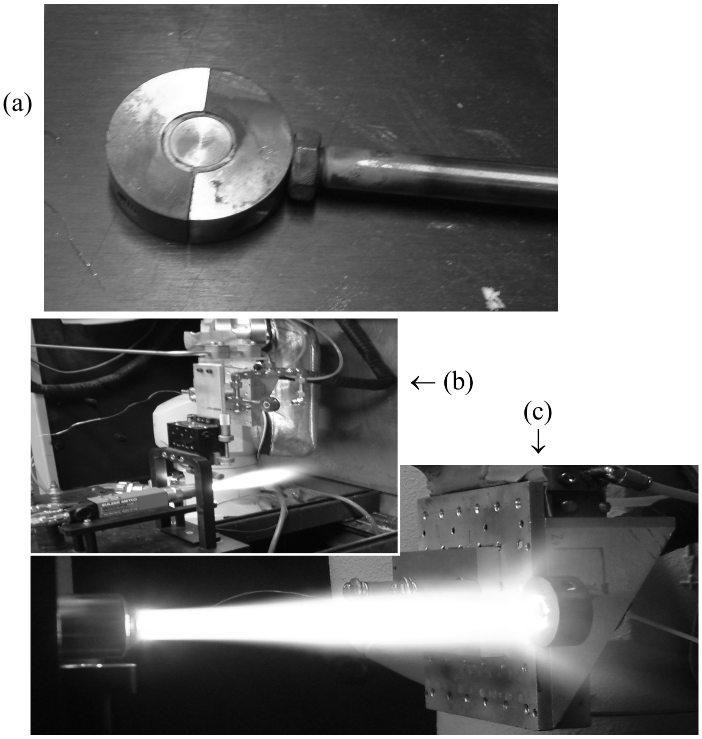


Figure 4: (a) Button calorimeter with 12.5 mm steel plug containing the thermocouples surrounded by ceramic insulation and photographs of calorimeter (b) cooling out of torch flame and (c) in the flame.

Two augmented central composite designs were used. The first explored the operating space of the 6P-D-GC, 6P-D-FC, 6P-K-GC, 6P-K-FC, and the PG-550 for a fixed, high air flow. The second explored the operating space, including air flow, for the PG-550 and both of the air caps with the 6P-K configuration. The run order was chosen randomly except for the selection of a center point as the first and last test in the series. The factors evaluated included the total combustible gas flow (TF), oxy-fuel ratio (OFR), standoff distance (SD), and air flow (AF). The OFR was varied from 1.5-2.5, TF was varied from 35.5-44.8 SLPM (75-95 SCFH), and SD from 139.7-190.5mm (5.5-7.5”). Air flow was fixed at 165 SLPM (350 SCFH) for the first experiment and varied from 47.2-142 SLPM (100-300 SCFH) for the second. Powder gas (air) was set at 4.7 SLPM (10 SCFH). No powder was sprayed for these experiments.

The effect of alumina-13% titania powder (Saint-Gobain-Norton, Worcester, MA) on surface heat flux was also examined using the 6P-D-GC hardware configuration. This powder is a fused and crushed ceramic with a mean particle size of 25 µm. The surface heat flux was calculated using SODDIT from thermocouple data collected with button calorimeters (Figure 4). The surface of the calorimeters were in the as machined state and not grit blasted.

Results and Discussion

Each of the hardware combinations were tested using the first designed experiment which examined the effect of TF, OFR and SD for a fixed, high AF of 165 SLPM (350 SCFH). An augmented central composite design was used for the 3 variables with many repeated center points for a total of 28 points. To verify the reproducibility, the 28 points were repeated a second time and found to be very similar.The PG-550 torch exhibited the highest average heat flux. The only hardware that had a significant effect on average overall heat flux was the air cap as shown in Figure 5. The flame cooling air cap for the 6P torch was found to decrease average surface heat flux to about 25% of the flux observed with the gun cooling air cap independent of nozzle selection. Because of the fixed, high AF which substantially cooled the flame, the heat flux of the 6P torch with the flame cooling air cap was less affected by stand off distance (SD) than by TF and OFR independent of nozzle selection. For both the 6P nozzles with GC air cap and the PG-550 torch, the heat flux significantly increased with total flow and decreased with OFR and SD (Figure 6).

The second designed experiment utilized an augmented central composite design having 31 points. This study was performed to further investigate the effects of air flow on surface heat flux. The 6P-K with both the gun cooling (GC) and flame cooling (FC) air caps and the PG-550 torches were evaluated to determine the effect of OFR, TF, SD, and AF. As before, the OFR was varied from 1.5-2.5, TF was varied from 35.5-44.8 SLPM, and SD from 139.7-190.5mm. In these experiments, the air flow was varied from 47.2-142 SLPM. Powder gas (air) was set at 4.7 SLPM. There was no statistical difference in average heat flux between the PG-550 and 6P-K-GC for the process conditions evaluated while the average flux for the 6P-K-FC was about half that of the others (Figure 7). As compared to the data for 165 SLPM air flow, the heat fluxes are considerably higher for all torch configurations and operating conditions.

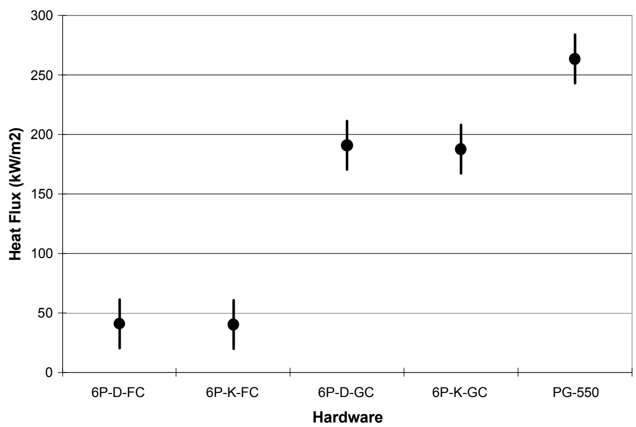


Figure 5: Average heat flux for different hardware configurations with fixed 165 SLPM cooling air flow

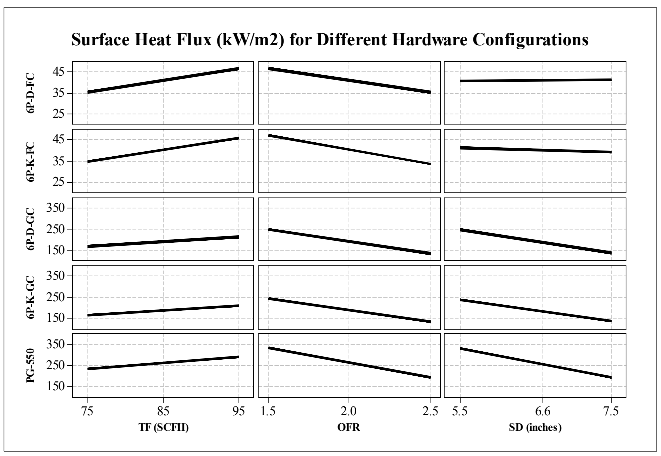


Figure 6: Surface heat flux (kW/m2) as a function of torch parameters for different hardware configurations with a set cooling air flow rate of 165 SLPM.

All of the torch operating parameters affected the heat flux significantly; however, air flow had the greatest impact on heat flux. The flame cooling air cap exhibited the most dramatic decrease in surface heat flux with increased air flow as expected due to more cooling air being transferred to the substrate. The heat flux increased with TF and decreased with OFR, SD, and AF for all hardware configurations as shown in Figure 8. For the 6P-K-GC, OFR, SD, and TF had more of an effect on heat flux than AF while for the 6P-K-FC, AF had the largest effect on heat flux. The PG-550 was affected similarly to the 6P-K-GC with the only difference being larger influence of AF.

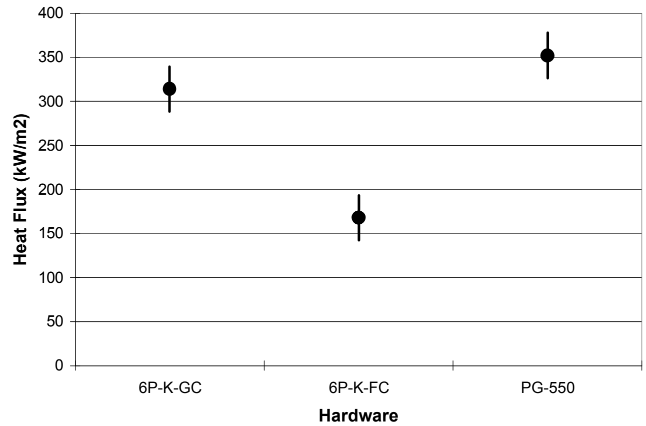


Figure 7: Effect of hardware configuration on overall average surface heat flux with cooling air flows ranging from 47 to 142 SLPM

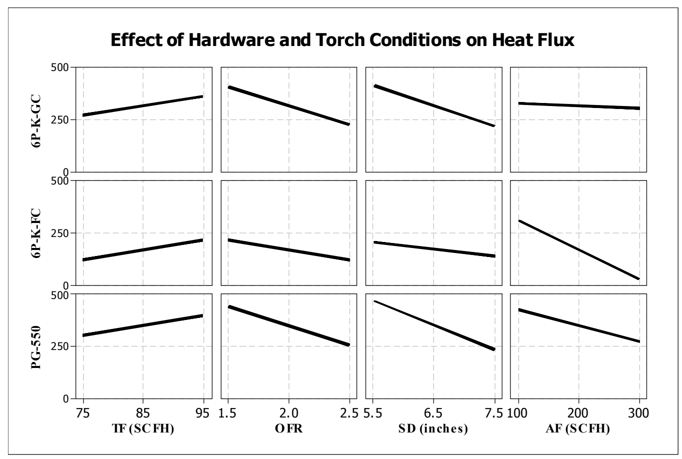


Figure 8: Surface heat flux (kW/m^2) as a function of torch parameters for different hardware configurations

The surface heat flux was much higher when alumina-titania powder was sprayed than during the flame-only tests. The 6P-D-GC torch was operated at TF = 35.5 SLPM (75 SCFH), OFR= 1.62, AF= 94.4 SLPM (200 SCFH), SD = 127mm (5"), powder gas = 4.7 SLPM, and a powder feed rate of approximately 12 g/min. The heat flux with powder was initially much larger due to the impact of melted particles onto the calorimeter and decreased as the coating built up as shown in Figure 9 and Table 1.

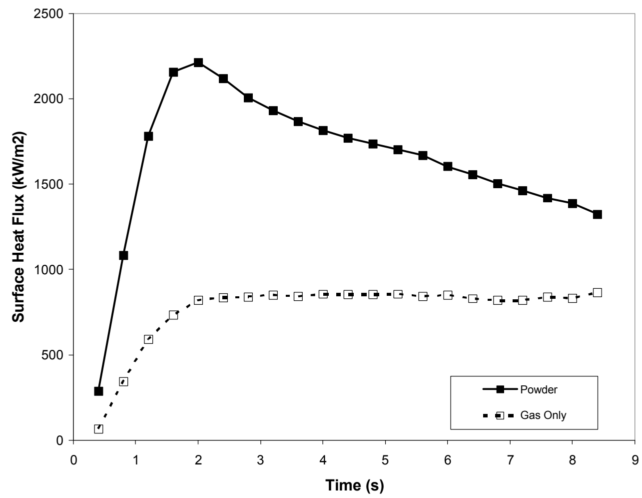


Figure 9: Effect of powder on surface heat flux of 6P-D-GC hardware configuration.

Table 1 Effect of Powder on Heat Flux for 6P-D-GC

Flame Type	Surface Heat Flux (kW/m^2)	
	Peak	**Average**
Gas-Only	866	841
Alumina-titania	2213	1736

Conclusions

The heat flux into the surface of a substrate during oxy-acetylene flame spraying is affected by hardware choice as well as process parameters. The geometry of the cooling air injectors has the greatest effect with air caps that direct cooling air toward the flame producing the lowest heat fluxes. When cooling air flow rate is low (less than 165 SLPM), the surface heat flux is considerably higher. The surface heat flux was relatively independent of torch nozzle configuration for low cooling air flow rates as the Sulzer Metco 6P and Alamo PG-550 exhibit similar fluxes. In general, surface heat flux increases with total flow of combustible gasses and decreased with oxy-fuel ratio, standoff distance, and cooling air flow. Powder initially increases the surface heat flux on a substrate then gradually decreases as the coating builds providing a thermal barrier.

References

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