SAND2007-3126C

DJ-2700 Hybrid HVOF Response Surface and Process Vectors

Dr. A. C. Hall, Mr. J. F. Mccloskey*
Sandia National Laboratories
Albuquerque, NM, USA

Keywords: Thermal Spray, Amorphous Coatings, High Velocity Oxy Fuel, Response Surface

Abstract

The behavior of A Sultzer-Metco Diamond Jet (DJ-2700) Hybrid HVOF torch was characterized while spraying a proprietary amorphous stainless steel powder. The primary goal of this characterization was to identify process vectors for the DJ-2700 HVOF torch and to characterize the Tp, Vp response surfaces around a potential operating condition. This paper describes the torch characterization and presents data from two designed experiments that identify the process vectors and measure the Tp, Vp response surface.

Introduction

A two part design of experiments approach was used to explore the operating space of the DJ-2700. First, the torch was fired and each flow meter was adjusted until the minimum and maximum practical settings were identified for oxygen, air, and fuel. The practical flow settings were determined as follows: The lower limit of each gas flow was found by reducing the gas flow until the torch no longer supported stable combustion. As combustion becomes unstable the torch sputters, whistles, and eventually goes out. The upper limit was determined by opening the rotometer valve until gas flow no longer increased. All experiments were conducted using gas flows that were within these boundaries. After determining the maximum and minimum practical gas flows for the DJ-2700 a 3^2 full factorial experiment was conducted. This experiment involved driving the torch to all min-max combinations of the oxygen, fuel, and air flows identified above and measuring particle temperature (Tp) and particle velocity (Vp) at each condition. This data was used to select a series of candidate operating conditions. The second part of the torch evaluation strategy involved a second designed experiment. This experiment was intended to provide a more thorough investigation of the response surface around the candidate operating condition. An augmented central composite design involving three factors (Total Flow of combustible gasses (TF), Equivalence ratio (Φ), and Standoff Distance) was used. Each factor was systematically varied over five levels while Tp, Vp, Tp stdev, and Vp stdev were measured.

Experimental Procedure

The DJ-2700 HVOF torch is an oxy-fuel torch consisting of a torch body, a siphon plug assembly, and a water cooling head. The torch body provides an attachment point for the incoming fuel, oxygen, air, and powder lines; and contains the main on/off gas valves for the torch. The siphon plug assembly contains the powder injector, mixing chamber for the combustible gasses, flame nozzle, and the combustion chamber. This portion of the torch mixes the combustion gasses and delivers them to the combustion chamber. The water cooling head contains the "air cap" which is simply a converging – diverging nozzle. The combustion gasses and entrained powder pass through the air cap and exit the torch. The water jacket provides cooling to the air cap, preventing it from melting during torch operation. Propane, Propylene, and Hydrogen can each be used to fuel the torch. Different torch hardware (powder injectors, siphon plugs, flame nozzles, combustion chambers, and air caps) must be used to accommodate different combustion gases. Sultzer-Metco provides one set of hardware for Propane and Propylene and a different hardware set for hydrogen. The Propane / Propylene hardware was used for all experiments reported here.

Inside the combustion chamber of the DJ-2700 torch at the flame nozzle there is a ring of oxy-fuel flames. Powder is injected into the combustion chamber along the centerline of this flame ring. Compressed air is injected into the combustion chamber concentrically around the outside of this flame ring. The entire particulate laden gas flow exits the combustion chamber through the water cooled "air cap". This results in hot (~2000°C), high velocity (~ 700 m/s) molten droplets being projected downstream toward the substrate where they deform and solidify to form a lamellar coating.

A Coriolis mass flow meter (Micro Motion; Boulder, CO) was used to verify the mass flow rate of oxygen, propane, and air through the DJ-2700 gas controller. The Sultzer-Metco DJ-2700 gas controller uses rotometers that read in units of (%); referring to percent of maximum gas flow. Verifying the mass flow meter allowed us to convert the flow meter readings (FMR) to units of Standard Cubic Feet Per Hour (SCFH).

All particle temperature (Tp) and particle velocity (Vp) measurements were taken using an Accura G3 Spray Sensor (Tecnar-Automation; St-Bruno, QC, Canada). Throughout all experiments the DJ-2700 torch was mounted in a fixed position, spraying horizontally. The Accura G3 was mounted on an optical rail allowing for standoff distance to be varied. Standoff distance for the Accura was measured using a ruler.

All experiments were conducted with a single lot of the stainless steel powder. A particle size analysis of this material made using a Beckman Coulter Laser Diffraction Particle Size Analyzer (Beckman Coulter, Fullerton, California). This particular stainless steel had a mean particle size of 43.21 microns and a standard deviation of 19.90 microns.

Results & Discussion

Equivalence ratio (Φ) is a somewhat unusual term. It can be thought of as a normalized oxy-fuel ratio. It is calculated from the oxygen, fuel, and air flows and gives an idea of the oxy-propane flame temperature. Equivalence ratio (Φ) is defined in equation (1).

$$\phi = \frac{(F/O)_{actual}}{(F/O)_{stoic\ \mathrm{hom}\ etric}} \qquad 1$$

Where F = fuel flow, O = oxygen flow. The stocihometric fuel to oxygen ratio for propane is 0.20. A thorough discussion of equivalence ratio can be found in [1]. If Φ < 1.0 the flame is fuel lean, if Φ > 1.0 the flame is fuel rich. Typically maximum flame temperatures are reached at Φ's slightly above 1.0.

Initial Full Factorial Screening Experiment

The minimum and maximum flow settings that were identified are shown in Table 1. When using this table it is important to understand that because of the gas dynamics inside the DJ-2700 oxygen flow and fuel flow are strongly dependent on each other. We did not explore this relationship. Higher oxygen and fuel flows may be possible in the DJ-2700.

Table 1 Minimum and maximum gas flows for the DJ-2700.

	Min (FMR)	Max (FMR)	Min (SCFH)	Max (SCFH)
Oxygen	20	40	302.25	591.97
Propane	20	30	333.20	503.23
Air	30	60	108.86	212.05

After determining minimum and maximum gas flows we conducted a 3^2 full factorial experiment as follows:

- Three factors: oxygen flow, propane flow, and air flow
    - Oxygen Flow: 302.2 – 591.9 SCFH
    - Propane Flow: 333.2 – 503.2 SCFH
    - Air Flow: 108.8 – 212.0 SCFH
- One center point repeated three times:
    - O2: 447.1 SCFH, Propane: 418.2 SCFH, Air: 160.4 SCFH
- Four responses:
    - 1 minute average particle temperature (Tp)
    - 1 minute average particle velocity (Vp)
    - 1 minute standard deviation of particle temperature (Tp stdev)
    - 1 minute standard deviation of particle velocity (Vp stdev)
- All experiments conducted in random order
- All Tp and Vp data collected at 13" standoff distance
- All Tp and Vp data collected by capturing data for 1 minute and taking average and standard deviations from this 1 minute data log.

The raw data from the 3^2 full factorial experiments are shown in Table 2. You will notice that not all of the planned oxygen – fuel flow combinations were reached. This was due to the limitations of the DJ-2700 torch. All data was collected at a standoff distance of 9 inches. Observed particle temperatures ranged from 1796°C to 2078°C. Observed particle velocities ranged from 467m/s to 715m/s. Particle temperature and particle velocity cannot be varied independently. Standard deviations ranged from 4.95°C to 50.68°C for Tp and 2.12 m/s to 69.17m/s for Vp. Fortunately, variations in Tp and Vp are correlated. Large variations in Tp are associated with large variations in Vp, showing that the DJ-2700 is more stable (more consistent Tp and Vp) at certain operating conditions.

Table 2 Raw data from the 3^2 full factorial experiment (all data taken at 9" standoff distance)

Run #	Oxygen	Fuel	Air	Oxygen	Fuel	Air	Tp	Vp	Tp stdev	Vp stdev
	Actual (FMR)			Actual (SCFH)			1 Minute Average		1 Minute stdev	
1	40	30	30	591.969	108.8641	503.2343	2073.362	675.267	10.253	10.397
2	20	26	30	302.249	95.1061	503.2343	1854.024	511.954	50.677	69.168
3	20	22	60	302.249	81.3481	1013.324	2003.627	636.177	6.986	7.403
4	20	30	60	302.249	108.8641	1013.324	1821.676	715.329	4.945	2.124
5	34	22	30	505.053	81.3481	503.2343	2067.538	572.439	9.251	27.826
6	30	25	45	447.109	91.6666	758.2793	2075.078	646.126	6.423	6.948
7	40	19	59	591.969	71.0296	996.3213	2131.41	650.483	7.558	8.692
8	30	25	45	447.109	91.6666	758.2793	2061.952	685.123	7.21	7.624
9	30	25	45	447.109	91.6666	758.2793	2071.256	588.952	15.301	40.618
10	40	15	58	591.969	57.2716	979.3183	2078.864	467.838	13.584	38.497
11	20	30	30	302.249	108.8641	503.2343	1796.071	590.449	16.473	17.785

This data was analyzed with Minitab 14 (Minitab Inc. State College, Pennsylvania) software using a regression approach. Analysis of the residuals shows that the Vp data meets the normality assumptions, but also shows evidence of non-normality in the Tp data. Better controlled experiments would be needed to eliminate the non-normality in the Tp data. Nevertheless this data does provide insight into the DJ-2700 process.

The main effects plots are shown in Figures 1 and 2. The analysis shows that Tp is significantly affected by the oxygen, and air flows. Increasing oxygen flow increases Tp, decreasing fuel flow decreases Tp, increasing air flow increases Tp. These effects are equivalence ratio effects. All three flows contribute to Φ; changing Φ, changes flame temperature and subsequently changes Tp. The analysis also shows that significant interactions between the air and fuel flows and the oxygen and fuel flows do exist and that they affect Tp.

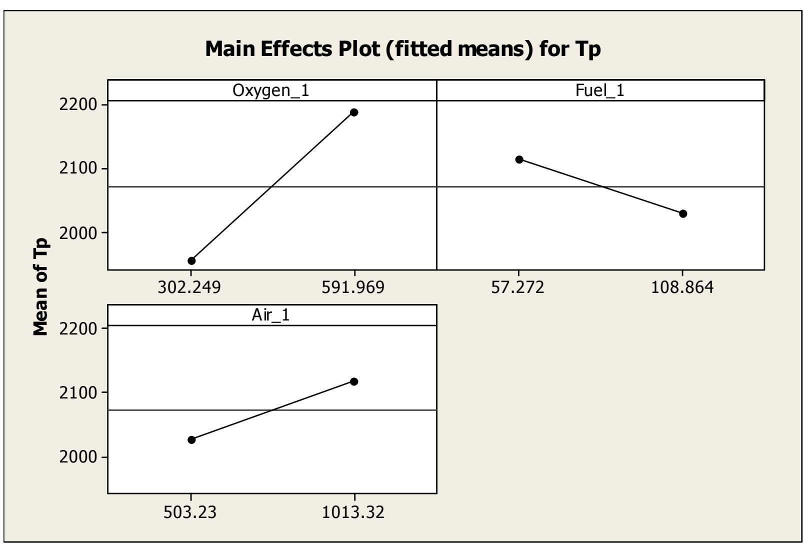

Figure 1 Main Effects plot for Tp showing that oxygen and fuel flows strongly affect Tp.

Figure 2 shows that fuel and air flows significantly affect Vp. Increasing fuel flow and / or air flow increases Vp. This is related to total flow of combustible gasses. As the total flow increases, the gas velocity through the nozzle increases, and Vp also increases. No significant interactions affecting Vp were detected in from this data.

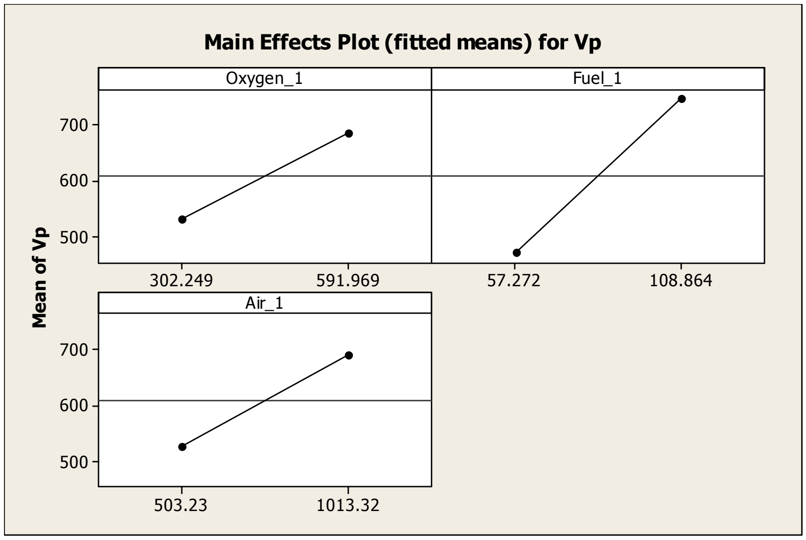

Figure 2 Main Effects Plot for Vp showing that fuel and air flows most strongly affect Vp

Figures 3 and 4 are cube plots showing Tp and Vp as a function of oxygen, fuel, and air flows. These plots were used to choose a condition for the response surface measurement. A condition showing high Tp and Vp as well as low variation in Tp and Vp was chosen.

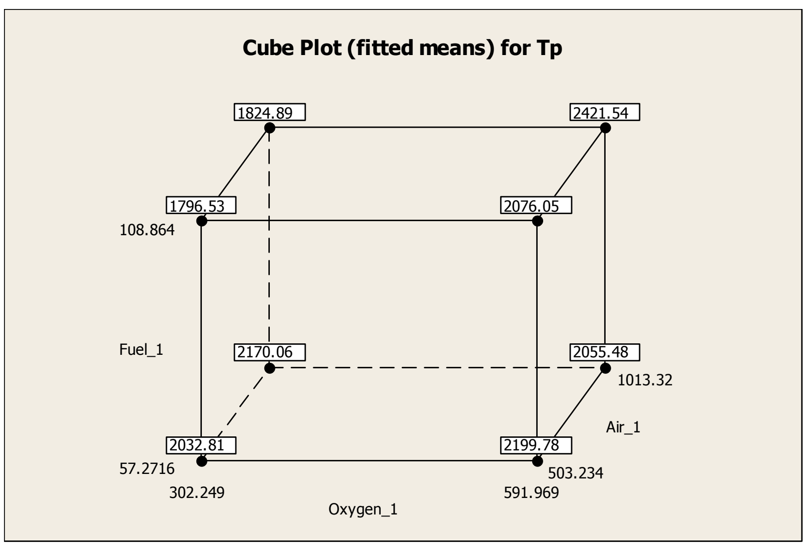

Figure 3 Cube plot showing Tp in Fuel, Oxygen, Air Space

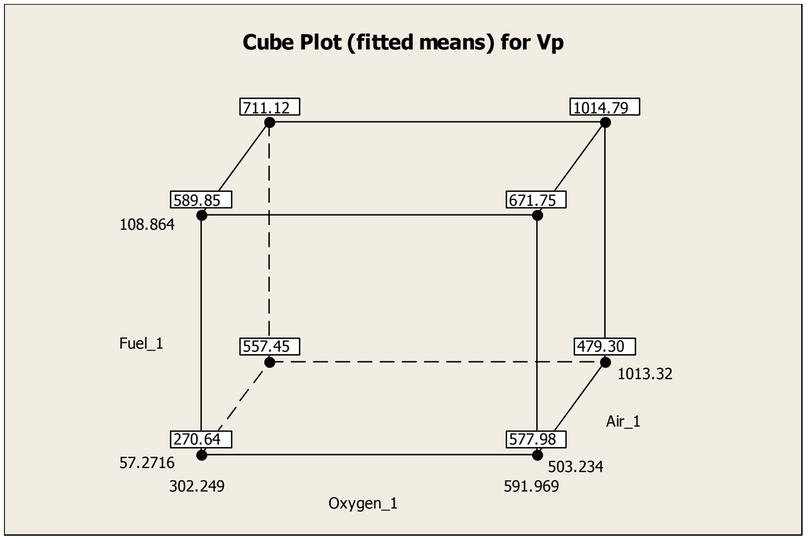

Figure 4 Cube plot showing Vp in Fuel, Oxygen, Air Space

Augmented Central Composite Designed Experiment & DJ-2700 Response Surface

We conducted an augmented central composite designed experiment about condition the chosen condition. This experiment was a 3^5 partial factorial experiment. Three factors were varied in this experiment; they are Total Gas Flow (TF), Equivalence Ratio (Φ), and standoff distance. Total flow is the sum of the air, fuel, and oxgen flows. Equivalence ratio was defined in equation (1) above. Standoff distance is simply the linear distance from the exit of the torch to the point of measurement or the substrate. Modeling of the gas dynamics in the DJ-2700 process by Li et. al. [2] explains that TF and Φ are largely independent process control vectors for Vp and Tp, respectively. The modeling presented by Li [2] motivated us to choose TF, Φ, and Standoff Distance as the factors for this experiment. This experiment does include three repeated center points so that complete statistical analysis can be performed. One (1) 2” x 2” witness coupon was hand sprayed at each of the 28 spray conditions. The experiment was blocked by standoff distance to save time. Blocking by standoff distance allowed us to move the Accura head only 5 times instead of 28 times. The conditions were run in random order within the blocks. The raw data from this experiment is shown in Table 3.

Table 3 Raw data from the Augmented Central Composite Designed Experiment

DOE Step #	Standard Order	Standoff Distance (in)	Total Flow (SCFH)	Φ	Tp (°C)	Vp (m/s)	Tp stdev	Vp stdev
1	13.00	9.64	1492.76	0.82	2047.96	705.99	5.74	2.457
2	16.00	9.64	1375.02	0.55	2060.35	632.20	6.52	2.034
3	22.00	9.64	1375.02	0.94	1969.74	661.28	6.22	1.74
4	25.00	9.64	1610.50	1.10	2102.92	688.04	6.48	3.182
5	26.00	9.64	1610.50	0.63	2099.70	652.50	7.44	4.448
6	5.00	11.00	1562.76	0.98	2071.99	610.33	8.67	3.302
7	17.00	11.00	1562.76	0.72	2089.40	616.87	10.52	28.691
8	18.00	11.00	1422.76	0.66	2067.65	566.60	7.88	24.821
9	23.00	11.00	1422.76	0.90	1962.31	650.59	22.00	17.473
10	1.00	13.00	1492.76	0.82	2073.15	588.01	6.44	4.176
11	2.00	13.00	1492.76	0.60	2095.00	537.04	7.57	5.462
12	4.00	13.00	1492.76	1.03	2045.51	594.91	5.22	3.829
13	6.00	13.00	1492.76	0.82	2079.68	560.04	7.54	6.553
14	8.00	13.00	1492.76	0.82	2059.60	501.74	15.79	36.872
15	11.00	13.00	1492.76	0.82	2081.44	539.74	8.47	10.74
16	14.00	13.00	1610.50	0.87	2086.86	438.71	17.15	65.196
17	19.00	13.00	1375.02	0.75	2055.92	513.47	9.40	4.865
18	24.00	13.00	1492.76	0.82	2073.34	511.31	8.93	15.892
19	28.00	13.00	1492.76	0.82	2074.48	565.10	9.70	4.842
20	7.00	15.00	1562.76	0.98	2106.69	507.31	7.08	3.331
21	15.00	15.00	1422.76	0.66	2113.68	433.73	7.90	4.61
22	20.00	15.00	1562.76	0.72	2111.19	459.53	9.61	16.3
23	21.00	15.00	1422.76	0.90	2049.06	525.31	8.32	5.801
24	3.00	16.36	1375.02	0.55	2098.79	406.52	7.41	2.559
25	9.00	16.36	1492.76	0.82	2097.53	479.95	7.16	6.263
26	10.00	16.36	1610.50	0.63	2127.77	413.57	6.19	2.835
27	12.00	16.36	1610.50	1.10	2117.34	428.29	6.01	4.032
28	27.00	16.36	1375.02	0.94	2069.04	457.05	6.91	3.004

The raw data shows that Tp varied from a maximum of 2117°C to a minimum of 1962°C and that Vp varied from a maximum of 705 m/s to a minimum of 413 m/s. Particle velocity clearly decreased as standoff distance increased as expected.

A response surface regression analysis was conducted for the Tp and Vp data shown in Table 3 using Minitab. Anderson-Darling normality tests on the residuals shows that the Tp data meets the normality assumptions and that evidence of non-normality exists in the Vp data. Better controlled experiments would be needed to eliminate the non-normality in the Vp data. Nevertheless, important conclusions can be drawn from this data.

The regression coefficients show that Φ is the only main effect significantly affecting and that TF and Standoff distance are the only main effects significantly affecting Vp. The interaction of standoff distance and TF and the interaction of TF and Φ also significantly affect Tp. The interaction of TF and Φ is the only interaction significantly affecting Vp.

Contour plots are an effective way to look at the response surface. They are shown in Figures 5 and 6. These response surfaces can be used to choose approximate TF, Φ, and SD conditions to produce a desired Tp or Vp.

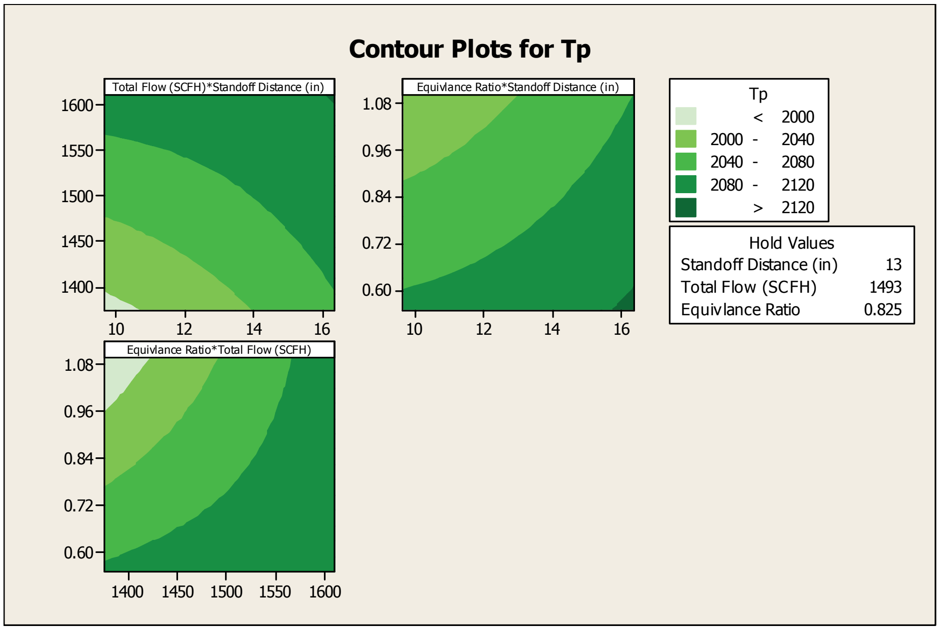

Figure 5 Contour plots of the Tp response surface

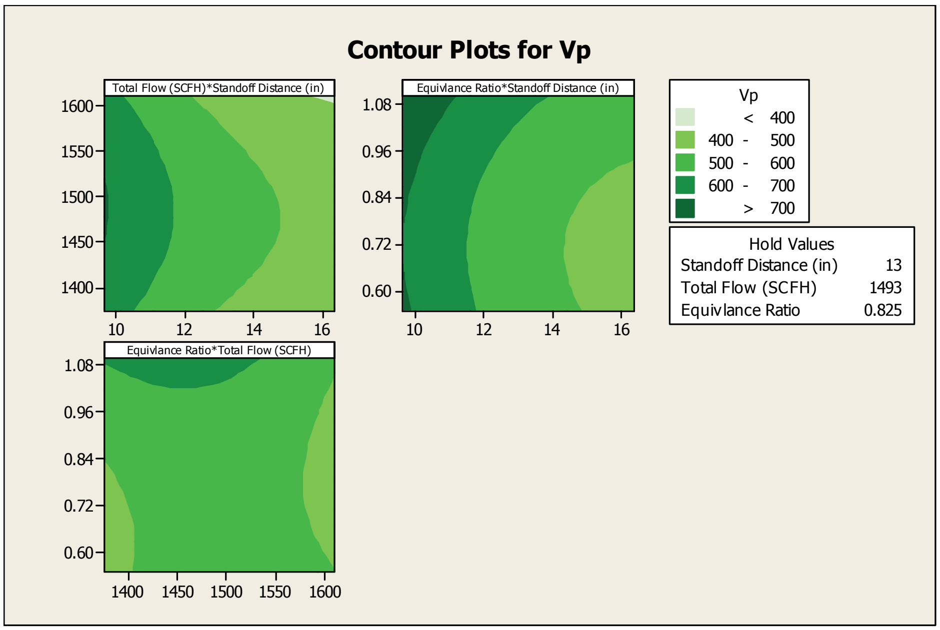

Figure 6 Contour plots for the Vp response surface

The response surface analysis allows Tp and Vp to be expressed mathematically in terms of TF, Φ , and SD. Those equations are shown below.

$$Tp = 48.30\ SD + 0.97\ TF - 1469.47\ \Phi + 0.40\ SD^2 + 12.08\ \Phi^2$$

$$-0.04\ SD*TF + 9.19\ SD*\Phi + 0.82\ TF*\Phi + 1384.21 \quad (2)$$

$$Vp = -108.9SD + 15.1TF + 686.4\Phi + 4.0SD^2 + 547.4\ \Phi^2 + 3.0\ SD*\Phi - TF*\Phi - 10005.6 \quad (3)$$

These equations can also be used to estimate gas flow conditions that will produce a given Tp and Vp when spraying this particular stainless steel using the DJ-2700 torch. They should be used with caution because they are necessarily dependent on the properties of the particular powder being sprayed.

Conclusions

Analysis of the Tp, Vp data from the augmented central composite design clearly verifies the conclusions reached by Li et. al [2] when they modeled the gas dynamics of the DJ-2700 hybrid HVOF torch. Vp is primarily affected by TF and Tp is primarily affected by Φ.

The Sulzer-Metco DJ-2700 Hybrid HVOF torch offers straight forward methods to control Tp and Vp (Φ and TF, respectively).

Acknowledgements

The authors would like to acknowledge the Naval Research Laboratory for supporting this work. We would also like to acknowledge A&A Corporation and Mr. Robert Rigney for allowing access to and providing assistance with characterization of their DJ-2700 Hybrid HVOF torch.

References

[1] Charles M. Hackett; Ph.D. Thesis, 1996, Pennsylvania State University, Department of Mechanical Engineering

[2] *Diamond Jet Hybrid HVOF Thermal Spray: Gas-Phase and Particle Behavior Modeling and Feedback Control Design*; Mingheng Li, Dan Shi, and Panagiotis D. Christofides; Ind. Eng. Chem. Res. 2004, 43, 3632-3652