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# Attachment A

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A Taguchi Experimental Design Study of Twin-Wire Electric Arc Sprayed Aluminum Coatings


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## Abstract

An experimental study was conducted on the twin-wire electric arc spraying of aluminum coatings. This aluminum wire system is being used to fabricate heater tubes that emulate nuclear fuel tubes for use in thermal-hydraulic experiments. Experiments were conducted using a Taguchi fractional-factorial design parametric study. Operating parameters were varied around the typical process parameters in a systematic design of experiments in order to display the range of processing conditions and their effect on the resultant coating. The coatings were characterized by hardness tests, optical metallography, and image analysis. The paper discusses coating qualities with respect to hardness, roughness, deposition efficiency, and microstructure. The study attempts to correlate the features of the coatings with the changes in operating parameters. A numerical model of the process is presented including gas, droplet, and coating dynamics.


**THERMAL SPRAYING IS A GENERIC TERM** that encompasses several material spraying processes: plasma spraying, combustion (flame) spraying, nozzle aspirated spraying, and twin-wire electric arc spraying.[1-3] The more common thermal spray coating functions include wear resistance, heat and oxidation resistance, corrosion resistance, electrical or thermal conductivity or resistivity, restoration of dimension, and clearance control.

Two-wire electric arc spraying was developed early in the 20th Century. In 1914, Schoop and his colleague Bauerlin performed their initial experiments with electric heating wires. The advantages of the two-wire arc are greater output and generally less cost to run than most alternative methods. Over the years, the physical size, efficiency, and throughput of two-wire electric arc devices have improved significantly. Although most two-wire electric arc systems run on direct current, alternating current versions have been introduced. Both dc and ac wire-arc spray devices have been developed in the Soviet Union. Notably, a three-wire device has been tried there to spray dissimilar types of wires.

In the electric arc spray process, two wires are brought together and an electric arc struck between them. Typical dc voltages are between 25 and 35 V with current ranging up to 350 A or more. The arc developed between the two wires causes the tips of the wires to melt. An atomizing gas is delivered to the wires in such a way as to strip off small droplets of molten metal. In this way, kinetic energy is delivered to the droplets. Typical delivery rates of air are 849.5 L/m to 1669 L/m scmm (30 to 60 scfm). As material is removed, additional material is supplied by a controlled means of delivering the wires. The rate at which the wires are delivered is determined essentially by the current in the arc. The spatial separation of the wires is determined by the voltage (i.e., the potential drop across the wires). For different materials, the optimal values of voltage, current, and air pressure can be determined, though typical values range from 25 to 35 V; 100 to 250 A; and 30 to 60 scfm of air (1699 L/m). Gases other than air may be substituted. Either nitrogen or argon may be sprayed to reduce the formation of oxide on the molten droplets. In general, any material that is electrically conductive and can be made into a wire can be sprayed with a twin-wire electric arc device.

Thermal spray technology is being used to fabricate heater tubes for thermal-hydraulic experiments.[4,5] These heater tubes are heated with a high-amperage dc power source to simulate nuclear fuel tube heat transfer. The heaters are fabricated using a multilayered coating system (metal bond coat, ceramic insulator, metal conductor, ceramic insulator, aluminum skin). Plasma spraying is used to fabricate the bond coat, conductor, and two insulator layers, while a twin-wire electric arc system is used to fabricate the heater skin.

The aluminum skin of the multilayered coating system has to withstand a water/steam environment and prevent any leakage to the inner conductor, which could result in shorting of the heater. Thus, a minimum porosity is required for the aluminum skin. Also, the heater requires the thermal properties of pure aluminum. The arc spray process was chosen for the ability to fabricate high-purity aluminum coatings, with high bond and interparticle strength. For this application, porosity and cracking of the aluminum are the most important microstructural features that must be controlled for the construction of durable heaters.

This work attempts to further the scientific understanding of the physical mechanisms involved in the formation of twin-wire electric arc metal coatings by determining which processing parameters affect the structure and properties of the coatings.

## Experimental Procedure

Taguchi experiments were used to optimize the aluminum skin layer of the heater tubes. Figure 1 illustrates a typical fabricated heater tube. A Hobart-Tafa twin-wire electric arc spray system and commercially available thermal spray aluminum wire (Tafa 01T) were used for this study.

Three Taguchi-style,[6] fractional-factorial L4 experiments were conducted. Each L4 experiment evaluated the effect of three processing variables on the quantitatively measured responses. System currents of 150, 250, and 300 A were used.

The quantitative Taguchi evaluation of the thermal spray process is ideal because it displays the range of measured coating characteristics attainable, and it statistically delineates the impact of each factor on the measured coating characteristics across all combinations of other factors. This information is useful in examining the physical science involved in thermal spray coatings, establishing realistic coating specifications, and developing new equipment. The Taguchi analysis was accomplished with personal-computer-based software[7] on the measured responses.

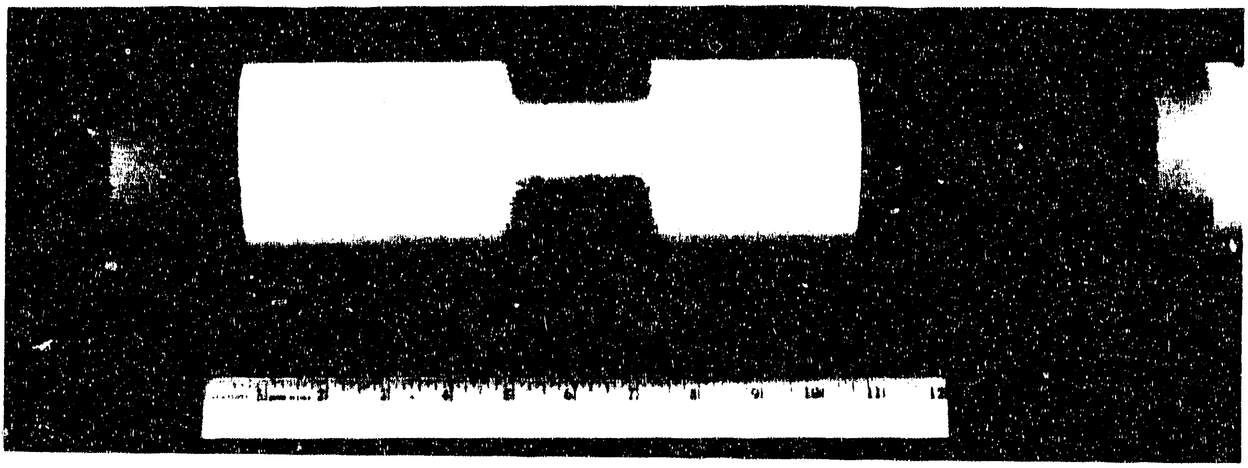


Fig. 1 - Heater tube.

Experiments TA01 through TA15 represent the fifteen experiments. In the Taguchi schemes, each variable has two levels selected to band around the nominal settings (i.e., Experiment TA01 for Experiments TA02 through TA05, Experiment TA06 for Experiments TA07 through TA10, Experiment TA11 for Experiments TA12 through TA15) in order to demonstrate the processing capabilities at a variety of stable thermal conditions. The experiments are detailed in Table 1. The parameters varied were primary air flow, spray distance, and gun traverse rate. Experiments TA01 through TA05 used a current of 150 A. Experiments TA06 through TA10 used 250 A. Experiments TA11 through TA15 used 300 A. The resulting responses evaluated were thickness (optical microscopy), superficial hardness (Rockwell 15T test), microhardness (Vickers test), porosity and coating roughness (image analysis), and deposition efficiency.

Using a Hobart–Tafa twin–wire electric arc spray system, the atomizing gas was air delivered to the two wires to strip off small droplets of molten metal. Wire feed was 9 lb/h for the 150–A experiments, 15 lb/h for the 250–A experiments, and 18 lb/h for the 300–A experiments. An x–y manipulator ensured the standoff distance and repeatability in the experiments. A y–step of 0.0032 m (0.125 in.) was used. Twelve traverses per pass were utilized. Three passes were used to fabricate the TA01 through TA05 coatings, while two passes were used to fabricate the TA06 through TA15 coatings. A system voltage of 28 V was used for all the experiments. The wire was thermal sprayed onto 6061 aluminum coupons [51 x 63 x 3 mm (2 x 2 x 0.125 in.)] cooled by air jets on the back side. One side of each steel coupon was grit blasted with No. 30 alumina grit before spraying.

## Materials Characterization Results

Table 2 lists the coating characterization results for this study.

The coating thicknesses, as revealed by optical metallographic observations at 300X magnification, are listed in Table 2. Average thicknesses from 12 measurements of the aluminum layers are listed, reflecting the influence of the various spraying parameters. Thickness per pass ranged from 3.2 to 10 mils (81 through 255 µm).

Porosity for the coatings, as revealed by image analysis, are listed in Table 2. A Dapple Image Analyzer with a Nikon Epiphot metallograph was used for the metallurgical mounts. Image analysis procedures were first tested for sensitivity to parameter variance. The average porosity of the aluminum coatings ranged from 2.7 to 6.2%.

Superficial Rockwell hardness and microhardness measurements were taken on the coatings. The superficial Rockwell hardness measurement was taken normal to the deposit using the 15T method. Microhardness measurements were taken on a cross–section through the coating. Twelve measurements were taken and averaged. The superficial Rockwell hardnesses ranged from 23 to 60, while the microhardness measurements ranged from 41.7 to 52.6.

Deposition efficiency for the experiments was determined with conventional techniques by measuring the amount of sprayed metal deposited for an allotted time. The deposition efficiencies ranged from 46.3 to 57.8%.

Table 1. Aluminum twin–wire electric arc Experiments TA01 through TA15.

| Experiment number | Taguchi | Current (A)[a] | Console P/Q[b,c] | Traverse rate[d] (in./s) | Traverse rate[d] (mm/s) | Standoff (mm) | Standoff (in.)[e] |
|---|---|---|---|---|---|---|---|
| TA01 | —[f] | 150 | 45/47.8 | 18.0 | 457.2 | 152.4 | 6.0 |
| TA02 | 1-1-1 | 150 | 40/43.8 | 15.0 | 381.0 | 127.0 | 5.0 |
| TA03 | 1-2-2 | 150 | 40/43.8 | 21.0 | 533.4 | 177.8 | 7.0 |
| TA04 | 2-1-2 | 150 | 50/50.5 | 15.0 | 381.0 | 177.8 | 7.0 |
| TA05 | 2-2-1 | 150 | 50/50.5 | 21.0 | 533.4 | 127.0 | 5.0 |
| TA06 | —[f] | 250 | 45/47.8 | 18.0 | 457.2 | 152.4 | 6.0 |
| TA07 | 1-1-1 | 250 | 40/43.8 | 15.0 | 381.0 | 127.0 | 5.0 |
| TA08 | 1-2-2 | 250 | 40/43.8 | 21.0 | 533.4 | 177.8 | 7.0 |
| TA09 | 2-1-2 | 250 | 50/50.5 | 15.0 | 381.0 | 177.8 | 7.0 |
| TA10 | 2-2-1 | 250 | 50/50.5 | 21.0 | 533.4 | 127.0 | 5.0 |
| TA11 | —[f] | 300 | 45/47.8 | 18.0 | 457.2 | 152.4 | 6.0 |
| TA12 | 1-1-1 | 300 | 40/43.8 | 15.0 | 381.0 | 127.0 | 5.0 |
| TA13 | 1-2-2 | 300 | 40/43.8 | 21.0 | 533.4 | 177.8 | 7.0 |
| TA14 | 2-1-2 | 300 | 50/50.5 | 15.0 | 381.0 | 177.8 | 7.0 |
| TA15 | 2-2-1 | 300 | 50/50.5 | 21.0 | 533.4 | 127.0 | 5.0 |

a. Gun current in amperes.
b. Console pressure in psia.
c. Console flow in liters/min.
d. Gun traverse rate in in./s.
e. Standoff distance in inches.
f. Equipment manufacturer's recommended process parameters.

Table 2. Coating characterization results for Experiments TA01 through TA15.

| Experiment number | Thickness (μm) | Thickness (mils) | Thickness/pass (μm/pass) | Thickness/pass (mils/pass) | Hardness[a] | Hardness[b] | Porosity (%) | Deposition Efficiency (%) | Roughness (μm) |
|---|---|---|---|---|---|---|---|---|---|
| TA01 | 363 | 14.3 | 122 | 4.8 | 15T49 | 45.4 | 4.8 | 51.1 | 5.70 |
| TA02 | 473 | 18.6 | 158 | 6.2 | 15T53 | 52.6 | 6.2 | 53.5 | 6.27 |
| TA03 | 244 | 9.6 | 81 | 3.2 | 15T54 | 50.8 | 4.4 | 46.3 | 6.00 |
| TA04 | 396 | 15.6 | 132 | 5.2 | 15T41 | 46.8 | 4.7 | 47.7 | 5.52 |
| TA05 | 366 | 14.4 | 122 | 4.8 | 15T53 | 46.3 | 5.7 | 54.8 | 5.55 |
| TA06 | 338 | 13.3 | 170 | 6.7 | 15T60 | 44.8 | 4.8 | 51.5 | 6.42 |
| TA07 | 440 | 17.3 | 221 | 8.7 | 15T34 | 41.7 | 5.0 | 57.0 | 7.51 |
| TA08 | 244 | 9.6 | 122 | 4.8 | 15T53 | 48.6 | 4.8 | 46.4 | 6.76 |
| TA09 | 368 | 14.5 | 186 | 7.3 | 15T57 | 41.9 | 3.0 | 49.0 | 5.94 |
| TA10 | 313 | 12.3 | 158 | 6.2 | 15T49 | 46.6 | 4.8 | 55.4 | 6.10 |
| TA11 | 424 | 16.7 | 214 | 8.4 | 15T43 | 44.4 | 3.4 | 52.8 | 5.85 |
| TA12 | 508 | 20.0 | 255 | 10.0 | 15T31 | 44.8 | 4.4 | 57.0 | 6.25 |
| TA13 | 315 | 12.4 | 158 | 6.2 | 15T37 | 44.1 | 4.0 | 49.0 | 6.73 |
| TA14 | 361 | 14.2 | 181 | 7.1 | 15T23 | 42.2 | 2.7 | 48.8 | 6.05 |
| TA15 | 391 | 15.4 | 196 | 7.7 | 15T27 | 44.0 | 3.7 | 7.8 | 7.65 |

a. Superficial Rockwell 15T hardness measurement. b. Vickers microhardness values (300–gram load).

Surface roughness was determined with image analysis. The data from each image was mathematically treated according to ANSI Standard B46.1, in which roughness is calculated as the average departure y from the mean height in a given region. The average departure y was determined for 20 frames, and the 20 frames were averaged to yield the final measured roughness. The roughness of the coatings ranged from 5.52 to 7.65 μm; higher values are rougher.

Image analysis revealed variances in the microstructures for the experiments. The combination of 50 psi console pressure, [381 m/s (15 in./s)] traverse rate, and [177.8 mm (7–in.)] spray distance produced thick coatings with the lowest porosity and roughness for each Taguchi experiment. Figures 2a, 2b, and 2c illustrate microstructures for coatings TA04, TA09, and TA14. Comparison of the coatings indicates that the porosity decreases with an increase in current (i.e., going from 150, to 250, to 300 A). Surface roughness for the three best coatings was not significantly different.

## Discussion of Taguchi Fractional Factorial Experiment Design

Taguchi fractional-factorial testing is a means to determin broad-based factor effects on measured attributes. This methodology statistically delineates the impact of each variable on the measured coating characteristics across all combinations of other factors.

The spray tests were conducted and evaluated once, and all data points were considered in the analysis of variance (ANOVA) calculations. The rho percent (p%) calculation indicates the influence of a factor or parameter on the measured response, with a larger number indicating more influence. The ANOVA calculations guide further experimentation by indicating which parameters are the most influential on coating attributes. This information is extremely useful in developing new coating specifications.

The optimum coating for this application in (as shown in Table 3 in order of priority) would have low porosity, high thickness, low roughness, high hardness, and a high deposition efficiency. Tables 3, 4, and 5 illustrate the results of the Taguchi analysis.

The Taguchi evaluation at 150 A indicated that spray distance was the most significant contributor to lowering porosity at 92 p%, with the longer standoff [177.8 mm (7 in.)] resulting in lower porosity. Other contributors were traverse rate at 7.5 p%, with the higher rate [533.4 mm (21 in./s)] resulting in lower porosity. The Taguchi evaluation at 250 A indicated that gun pressure and spray distance were the most significant contributors to lowering porosity at 37.9 p% for each, with the longer standoff [177.8 mm (7 in.)] and higher gun pressure (50 psia) resulting in lower porosity. Traverse rate had a 24.2 p%, with the lower rate [381 mm/s (15 in./s)] resulting in lower porosity. The Taguchi evaluation at 300 A indicated that gun

Table 3. Results of the Taguchi aluminum analysis (150 A).

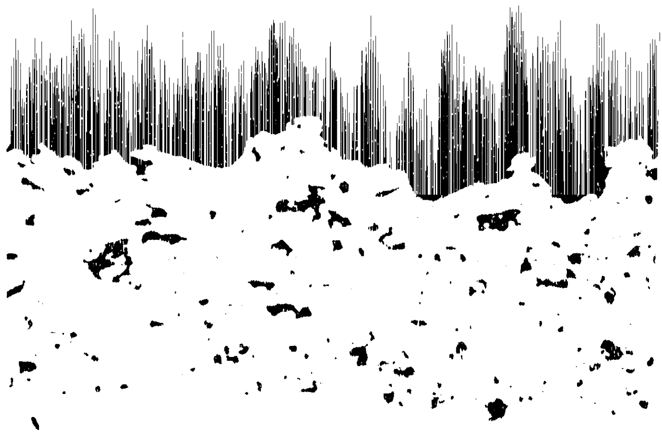
| Desired attribute | Gun pressure (p%/psia) | Processing factor: Traverse rate (p%/in./s) | Processing factor: Spray Z (p%/in.) |
|---|---|---|---|
| 1 Low porosity | 0.5/50 | 7.5/21 | 92.0/7 |
| 2 High thickness | 1.9/50 | 61.9/15 | 36.2/5 |
| 3 Low roughness | 90.7/50 | 3.6/21 | 5.7/7 |
| 4 High hardness (Rockwell). | 36.8/40 | 36.8/21 | 26.4/5 |
| 5 High microhardness | 93.8/40 | 4.7/15 | 1.5/5 |
| 6 High deposition efficiency | 3.4/50 | 0/15 | 96.6/5 |

Table 4. Results of the Taguchi aluminum analysis (250 A).

| Desired attribute | Gun pressure (p%/psia) | Processing factor: Traverse rate (p%/in./s) | Processing factor: Spray Z (p%/in.) |
|---|---|---|---|
| 1 Low porosity | 37.9/50 | 24.2/15 | 37.9/7 |
| 2 High thickness | 0.0/40 | 76.4/15 | 23.6/5 |
| 3 Low roughness | 80.9/50 | 5.7/21 | 13.5/7 |
| 4 High hardness (Rockwell) | 29.8/50 | 10.0/21 | 60.2/7 |
| 5 High microhardness | 2.3/40 | 94.3/21 | 3.4/7 |
| 6 High deposition efficiency | 0.3/50 | 5.7/15 | 93.9/5 |

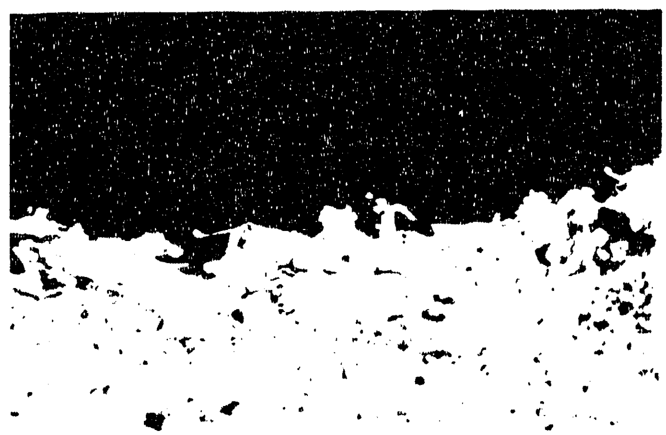
Table 5. Results of the Taguchi aluminum analysis (300 A).

| Desired attribute | Gun pressure (p%/psia) | Processing factor: Traverse rate (p%/in./s) | Processing factor: Spray Z (p%/in.) |
|---|---|---|---|
| 1 Low porosity | 69.5/50 | 3.9/15 | 26.6/7 |
| 2 High thickness | 6.2/40 | 32.5/15 | 61.3/5 |
| 3 Low roughness | 8.5/40 | 70.9/15 | 20.6/7 |
| 4 High hardness (Rockwell) | 75.7/40 | 23.4/21 | 0.9/7 |
| 5 High microhardness | 49.4/40 | 8.2/21 | 42.4/5 |
| High deposition efficiency | 0.1/50 | 0.3/21 | 99.5/5 |



(2a) TA04

(2b) TA09



(2c) TA14

Fig 2 – Optical photomicrographs of as–sprayed coatings (200X) TA04, TA09, TA14.

pressure was the most significant contributor to lowering porosity at 69.5 ρ%, with the higher gun pressure (50 psia) resulting in lower porosity. Spray distance had a 26.6 ρ%, with the longer standoff [177.8 mm (7 in.)] resulting in lower porosity.

Coating thickness buildup is dominated by the wire feed rate, which is dictated by the current of the system. Higher current results in higher wire feed and thicker coatings. Comparison of the mils per pass deposited for the cases which held all variables constant and then increased current (e.g., Tests TA01, TA06, TA11; Tests TA02, TA07, TA12) indicate this trend. The Taguchi evaluation at 150 A indicated that the lower level of the gun traverse rate was the most significant contributor to increasing thickness at 61.9 ρ%; the shorter spray distance [127 mm (5 in.)] was next most significant with 36.2 ρ%. The Taguchi evaluation at 250 A indicated that traverse rate was the most significant contributor to increasing thickness at 76.4 ρ%, with the slower traverse rate [381 mm/s (15 in./s)] resulting in greater thickness. The other main contributor was spray distance at 23.6 ρ%, with the shorter standoff [127 mm (5 in.)] resulting in greater thickness. The Taguchi evaluation at 300 A indicated that spray distance was the most significant contributor to increasing thickness at 61.3 ρ%, with the shorter distance [127 mm (5 in.)] resulting in greater thickness. The other main contributor was traverse rate at 32.5 ρ%, with the slower traverse [381 mm/s (15 in./s)] resulting in greater thickness.

Surface roughness was most influenced by using the higher level for gun pressure at 150 A with a 90.7 ρ%. The Taguchi evaluation at 250 A also indicated that primarily higher gun pressure (80.9 ρ%) and secondarily longer spray distance (13.5 ρ%) would result in a smoother coating finish. The Taguchi evaluation at 300 A indicated that using the lower level for the gun traverse rate would have the most significant impact, lowering roughness at 70.9 ρ%. Spray distance had a 20.6 ρ%, with the longer standoff [177.8 mm (7 in.)] resulting in lower roughness.

Superficial hardness increase (i.e., Rockwell) was equally influenced by the lower level for gun pressure (36.8 ρ%), and the upper level for the gun traverse rate (36.8 ρ%) at 150 A. The Taguchi evaluation at 250 A indicated that longer spray distance (60.7 ρ%) would result in a harder coating. Using the lower level for the gun pressure (75.7 ρ%), and using the upper level for the gun traverse rate (23.4 ρ%) would increase hardness at 300 A.

Microhardness increase (i.e., Vickers) was most influenced by the lower level of the gun pressure at 150 A. Using the upper level for the gun traverse rate dominated the hardness increase at 250 A. The Taguchi evaluation at 300 A indicated that the lower level for the gun pressure (49.4 ρ%) and the spray distance (42.4 ρ%) would result in harder coatings.

The Taguchi evaluation indicated that spray distance completely dominated the other process parameters for deposition efficiency. Shorter spray distance resulted in higher deposition efficiency: 96.6, 93.9, and 99.5 ρ% were obtained for the 150–, 250–, and 300–A experiments, respectively.

Selection of the optimum levels of the design factors can produce an optimum coating for this particular application. This coating would have low porosity, high thickness, low roughness, high hardness, and high deposition efficiency. This coating can be obtained by using a gun pressure of 50 psia (air flow of 50.5 L/m), a spray distance of [177.8 mm (7 in.)], and a traverse rate of 381 mm/s (15 in./s) for all three power levels.

## Numerical Modeling of The Twin-Wire Electric Arc Process

A spray-laden gas flow can be numerically modeled using spray models embedded in computational fluid dynamic (CFD) codes. Such codes typically compute the Eulerian gas flow field along with a set of Lagrangian-based particle flight patterns. Such particle flight paths may represent either a single particle or a cluster of particles. Fluid dynamic and particle models derived to represent the dynamics of a dilute dispersed phase in a gas flow field have been proposed by Crowe, Sharma, and Stock,[8] Gosman and Ioannides,[9] and Zhou and Yao,[10] among others.

The main features of the model of Zhou and Yao[10] have been implemented in a two-dimensional, compressible, axisymmetric, turbulent flow CFD code. The code belongs to the TEACH (Gosman and Ideriah[11]) family of codes and employs the standard k-e turbulence model. Conditions approximating the spray from a twin-wire electric arc spray gun have been modeled using the spray code. The inlet conditions for the spray code are obtained by idealizing the liquid spray-laden gas flow as it leaves the gun. Flow from the spray gun exit jet is assumed to be fully expanded with centerline Mach numbers = 0.95 and seeded with a distribution of liquid droplets from 19 to 120 mm at 2400 K.

The model of Zhou and Yao assumes that clusters of same-size particles travel in flight paths characteristic of a single particle of that size. The local spatial distribution of particles in the cluster is assumed to be Gaussian and to disperse radially from the cluster center as it travels downstream. Their model also allows the turbulence to affect the flight path of the cluster by superimposing a random turbulent velocity upon the mean particle velocity.

Experiment TA04 was modeled. Figure 3 illustrates the flight paths of 15 clusters of pure aluminum particles within the aforementioned size range. As the particles travel toward the target, they lose thermal energy to the surrounding air. The energy lost is modeled in the code based on the local Reynolds numbers of the particles. The material in each cluster of particles is assumed to be at a uniform temperature. Figure 4 illustrates the drop in temperature of each particle cluster as a function of axial distance. The temperature of each particle decreases until it reaches the solidification temperature and then remains constant as the material solidifies. The smaller particles lose energy faster because they have less mass to cool. The mass fraction of particles that have reached the solidification temperature before hitting the target is about 40%. While the current CFD spray code employs the main features of the model of Zhou and Yao, the model should be developed further to yield results that accord satisfactorily with experimental data.

The BUILD coating dynamics computer program employed in this study uses the particle data generated by the CFD code at the standoff distance to calculate the dynamics of the coating buildup. The code calculates the morphology of the injected particles one at a time and accumulates the results. As the particles are accumulated into the coating calculational matrix, the code calculates the coating thickness, porosity, and the average temperature and velocity of the impacting particles in the coating matrix. Details of the BUILD code are available in Reference 12.

The thickness of sample TA04 was measured with image analysis to be 396 μm (15.6 mils), while the porosity was measured to be 4.7%. The BUILD code calculated the thickness to be 373 μm (14.7 mils) and the porosity to be 3.7%. The average temperature and velocity of the 552 particles that hit the matrix were 1256 K and 54 m/s. Of the 552 particles that hit the matrix, 369 were between 19 to 24 μm, 78 were between 24 to 29 μm, 54 were between 29 to 50 μm, and 51 were between 50 to 120 μm.

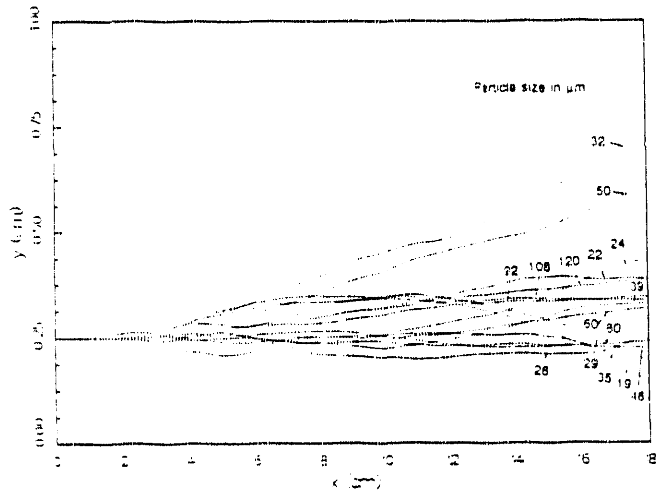


Fig. 3 - Predicted particle cluster trajectories for Experiment TA04.

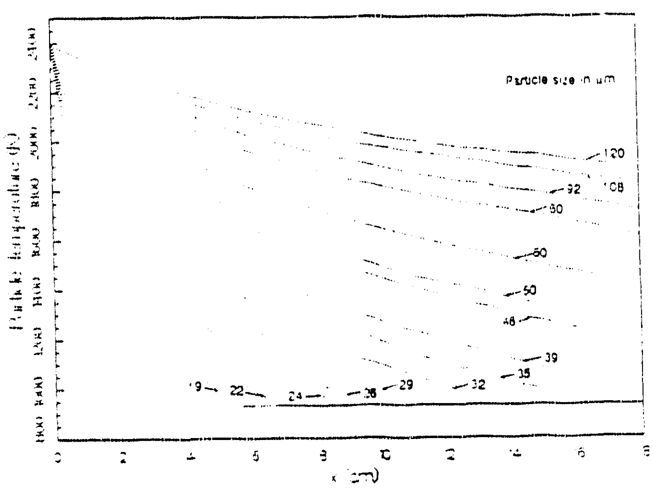


Fig. 4 - Predicted particle cluster temperatures as a function of axial location in the plume for Experiment TA04.

## Summary and Conclusions

An experimental study of the twin-wire electric arc spraying of aluminum wire has been presented. Experiments employed a Taguchi fractional-factorial approach with typical process parameters. The coatings were characterized by hardness tests, surface roughness, and optical metallography. Coating qualities were determined with respect to thickness, roughness, hardness, porosity, deposition efficiency, and microstructure.

The aluminum coating thicknesses, reflecting influences of spraying parameters, ranged from 81 to 255 μm/pass (3.2 to 10 mils/pass). Porosity for the coatings, as revealed by image analysis, ranged from 2.7 to 6.2%. The superficial Rockwell hardnesses ranged from 23 to 60, while the microhardness measurements ranged from 41.7 to 52.6. The deposition efficiencies ranged from 46.3 to 57.8%. The roughness of the coatings ranged from 5.52 to 7.65 μm.

The Taguchi evaluation indicated that to lower porosity, spray distance should use the higher level at 150 A, gun pressure and spray distance should use the higher levels at 250 A, and gun pressure should use the higher level at 300 A. The Taguchi evaluation at 150 and 250 A indicated that the lower level for the gun traverse rate was the most significant contributor to increasing thickness. At 300 A, the lower level for the spray distance was the most significant contributor to increasing thickness. Surface roughness was most influenced by the higher level gun pressure at 150 and 250 A. The Taguchi evaluation at 300 A indicated that the lower level for the traverse rate would have the most significant impact lowering roughness. Superficial hardness increase (i.e., Rockwell) was equally influenced by the lower level for gun pressure and the higher level for the gun traverse rate at 150 A. The Taguchi evaluation at 250 A indicated that the higher level spray distance would result in harder coatings. Using the lower level for gun pressure (75.7 ρ%), and the higher level for the gun traverse rate (23.4 ρ%) would increase hardness at 300 A. Microhardness increase was most influenced by using the lower level for gun pressure at 150 A, the higher level for the traverse rate at 250 A, and the lower level for gun pressure and spray distance at 300 A. The lower level for spray distance resulted in higher deposition efficiency for all three Taguchi experiments. An optimum coating for this particular application can be obtained by using a gun pressure of 50 psia, a spray distance of 177.8 mm (7 in.), and a traverse rate of 381 m/s (15 in./s) for all three powers.

The numerical model of the process, which included gas, droplet, and coating dynamics, is considered to be a first approximation of the dynamics occurring in the process. Further development of the model will be required before it will yield results that correlate more satisfactorily with experimental data.

The objective of this and future work is to optimize aluminum coatings. The range of coating attributes generated through the methodology presented in this paper serves to optimize the process and ultimately the coatings. From this statistical methodology, processing parameters can be adjusted, optimized, and confirmed and reliable and repeatable coating specifications can be established. The procedure described in this paper will also assist in selecting and optimizing operational parameters for future metal thermal spray processing experiments and applications for the twin-wire electric arc process.

## Acknowledgments

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