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Development of a Thick Wear-Resistant Jet Kote* Coating Produced at High Deposition Rate: A Technical Note

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The JET KOTE coating process is a high-velocity oxyfuel process used to form coatings of high quality and density. Coatings can be produced from carbide-bearing composite, alloyed metallic, nonmetallic, intermetallic, or pure metal powders. The coatings are used for wear and/or corrosion resistance in the aircraft, chemical, oil and gas, and steel manufacturing industries, as well as in other demanding fields. Many applications, especially in the petrochemical field, require thick coatings. Coatings must be applied economically, without loss of integrity. Thickness limitations are thought to be due to coating stress, which results in coating cracks and/or delamination and ultimately in failure. This paper examines the effects of operating parameters and techniques on the physical properties of thick coatings produced from Stelcar JK117, a tungsten carbide/17% Co composite powder. Special emphasis is placed on those parameters which are economically desirable to achieve high deposition rates.

1. Introduction

THE JET KOTE process introduced high-velocity oxyfuel (HVOF) coatings to the public in the early 1980s (Ref 1-3). Since then, HVOF coatings have significantly influenced and expanded the thermal spray market. Improvements in process control, materials science, and application development have been significantly supported by the aircraft industry. Current industry growth indicators favor nonaircraft applications, and although coating performance remains important, the application cost of the coating often dictates selection of the coating and process. The HVOF coating must be competitive with alternative surfacing methods. The cost of coating application is especially critical when thick coatings or coverage of large surfaces is required. The objective of this paper is to examine the technical problems of producing thick coatings, evaluate key factors that contribute to coating cost, and establish whether coating properties are affected by cost reduction methods.

2. Experimental Procedure

2.1 *Material*

Stelcar* JK*117, a tungsten carbide/17% Co composite powder, was selected for this research because many variations of the coating are in multiple use in the field. However, the coating is produced at low spray rates, and the behavior of the alloy has been studied only at thicknesses typically less than 0.76 mm (0.03 in.).

Keywords: High-velocity oxyfuel, JET KOTE, tungsten carbide, thick coating, wear resistance

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* JET KOTE, Stelcar, and JK are trademarks of Stoody Deloro Stellite, Inc., Goshen, IN.

2.2 *Baseline Coatings*

Baseline coating property data were obtained from coatings produced by the use of three JK117 parameters (Ref 4) with conventional and increased coating thickness and powder feed rates. The coating thickness limit is thought to be 0.5 mm (0.02 in.) when applied with set A conditions; no limit has been defined for set B and set C conditions (see Table 1). The powder feed rate range is 1.8 to 4 kg/h (4 to 9 lb/h) for these parameters. Gas flow rates and nozzle recommendations are given in Table 1.

2.3 *Equipment*

The JET KOTE IIA, a closed-loop mass-flow-controlled system, was used to produce the coatings. A carbide insert with a 2 mm (0.08 in.) opening was used so that powder feed rates greater than 4.5 kg/h (10 lb/h) could be achieved. A new torch design was used. The design changes were found to have no influence on coating properties.

2.4 *Design of Experiment (DOE)*

An L8 Taguchi (Ref 5, 6) DOE, containing two repetitions, was developed to establish statistical probability relationships between process variables and coating mechanical properties. The experiment was managed by a computer program called SADIE (Randy Culp, G.E. Medial Systems, Milwaukee, WI) (Ref 7). The Taguchi variables and levels are presented in Table 2.

2.5 *Response Measurements*

2.5.1 Measurement of Coverage Factors

A 140 mm (5.5 in.) portion of a 178 mm (7 in.) long by 44.5 mm (1.75 in.) diameter tube with a wall thickness of 64 mm (¼ in.) was coated using mechanical torch manipulation. The amount of powder used to coat the 0.02 m^2 (0.21 ft^2) area and the average thickness produced for each run were measured. The

Table 1 Gas flow and nozzle recommendations

	Gas flow, SCFH				
Set	O_2	C_3H_6	H_2	Ar	Nozzle
A	1000	137	...	57	5/16-6
B	580	...	870	57	1/4-6
C	570	...	1150	57	1/4-9

Table 2 L8 Taguchi DOE

Position	Variable	Level 1	Level 2
1	Powder feed rate, kg/h (lb/h)	2.3 (5)	9.1 (20)
2	Thickness, mm (in.)	0.38 (0.015)	0.76 (0.030)
3	Thickness per pass, mils	<1	1-2
4	Spray distance, cm (in.)	17.8 (7)	28.0 (11)
5	Cooling	Yes	No
6	Nozzle	1/4-6	1/4-9
7	Gas flow (Table 1)	Set B	Set C

data were converted to a coverage factor of the material required to apply a 0.25 mm (0.01 in.) thick coating to a 1 ft^2 (i.e., lb/ft^2/0.01 in.). Deposit efficiency was also determined.

2.5.2 Coating Stress

Standard 30N Almen (Ref 8) stress test panels, 25 by 75 by 0.76 mm (1 by 3 by 0.03 in.) thick, were rotated on a 165 mm (6.5 in.) diameter arbor affixed to a plate on one end and held flat by light pressure of a washer on the opposite end. The panels were allowed to expand in length, but remained relatively flat during heating and application of the coating. The surface was prepared by light grit blasting both sides of the panels with #60 aluminum oxide grit until they were as near to ±0.000 mm (±0.000 in.) flatness as could be measured. The deflection of the panel was measured with a dial indicator.

Deflection of the coating and panel was determined by measuring the direction and amplitude of panel deflection at the highest point, usually the center of the panel, and discounting panel and coating thickness. Coating stress—defined as neutral, tensile, or compressive, was determined by the direction of deflection of the panels (Ref 9). The magnitude of the stress was measured by the deflection amplitude. Neutral stress occurs when the panel and coating are flat and no deflection of the panel can be detected. Tensile stress occurs if the center of a coated panel, coating side up, deflects away from the ends of the panel. Compressive stress occurs when the center of the panel is raised and the ends of the panel are deflected away. Three stress values for each run were recorded.

2.5.3 Mechanical Properties and Coating Structure

Two panels of 1018 steel, 3.2 mm (1/8 in. thick, were coated while rigidly fixed beside the stress panels. Coating hardness data were obtained from each panel and the coating cross section examined at 100× and 200× magnification to determine levels of porosity, cracks, and inclusions. Superficial 15N and 300 g diamond pyramid hardness (DPH) tests were performed in accordance with ASTM standard practices (Ref 10, 11).

2.5.4 Coating and Substrate Temperature

The maximum temperature of the specimens was recorded using a standard digital contact pyrometer on the coated surface of the specimens immediately following application of the coating.

2.5.5 Coating Delamination and Cracking

All samples were examined for the appearance of delamination at the coating edges, voids at the interface, complete or partial separation of the coating from the substrate, or cohesive separation of the coating. A weighting procedure, adding a numerical value of 5 to each sample set for every specimen of that set observed to have the appearance of delamination, was adopted. Coating thicknesses of 0.38, 0.76, and 1.5 mm (0.015, 0.03, and 0.06 in.) were examined.

A value of 0 to 10 was also given to each sample set in order to estimate the severity of cracking. Zero defined no detected cracks, and 10 defined the appearance of the most severely cracked specimen observed. It was observed that in some of the sample sets, the coating cracked on flat specimens, but not on the tubes. For other coating sets, the reciprocal response was exhibited. The cumulative numerical values were recorded for each sample set along with specimen type.

2.5.6 Optimization Procedure

Confidence in the computer-generated statistical model was achieved by performing several runs to confirm model predictions of desirable and nondesirable coating properties. In addition, several single-factor arrays were tested to further refine coating properties with respect to economy at high powder feed rates.

3. Results

Tables 3 and 4 summarize the effect of process variables on coating properties, as predicted by the computer model. The numerical values produced by the computer model have been translated using a weighting procedure to summarize the significance and relationship of the process variables on coating properties.

Differentiating coatings by examination of structure was difficult due to their strong similarity. The coating observed to have the most defects, such as porosity, is shown in Fig. 1.

Table 3 DOE Responses(a)

Variable	Property: Coverage	Deflection	Temperature	15N	DPH	Structure
Powder feed rate		S				
Thickness						
Thickness per pass				L		
Spray distance	V	S	V	V	S	
Cooling			L			
Nozzle	V			L		
Gas flow		V	V	V	V	

(a) V, very significant; S, significant; L, less significant;. A blank space indicates inconclusive results.

Table 4 Responses that limit coating thickness(a)

Variable (0.03 in.)	Delamination for a thickness of: 0.76 mm (0.06 in.)	1.5 mm (0.03 in.)	Cracking for a thickness of: 0.76 mm (0.06 in.)	1.5 mm
Powder feed rate		L	S	V
Thickness		V		L
Thickness per pass		L		L
Spray distance			L	S
Cooling		L	L	L
Nozzle				
Gas flow		L	S	

(a) V, very significant; S, significant; L, less significant;. A blank space indicates inconclusive results.

4. Discussion

The JET KOTE process allows thick coatings to be produced by increasing the powder feed rate. However, viable coatings may not always be produced by using the same parameters as those recommended for thin coatings. The prime concern is to avoid spray problems associated with the torch as well as coating defects, including excessive porosity, cracks, and delamination.

The first successful thick JK117 coating, produced at a powder feed rate of 6.8 kg/h (15 lb/h), required the use of a 2 mm (0.08 in.) insert and set C conditions (Table 1). A coverage tube was successfully coated to a thickness of 3 mm (0.12 in.). However, attempts to use the same procedure to coat a flat panel resulted in severe coating cracking at a thickness of approximately 1.5 mm (0.06 in.). A procedure to coat any shape with the same method, reducing the time to build up the coating and cost without sacrificing quality, was developed via a designed experiment.

4.1 *Experiment*

Hydrogen was used as fuel because it allows exploration of a broader range of process variables than carbon-base fuels. The gas flow and nozzle selection for low powder rates are shown in Table 1 (Ref 3). Gas flow conditions B and C were used in the DOE. Other variables, such as total gas flow and fuel-to-oxygen ratio, which contribute to the cost and may also influence coating properties, was not explored. Key variables thought to affect JK117 coating properties fit well into the L8 Taguchi format. Table 2 lists the levels and assigned positions for the DOE.

4.2 *Results*

The response data included coverage data in lb/ft^2/0.01 in. and typical coating property data. Following confirmation of the Taguchi model, coating defects and coverage responses caused by changes in parameters were predicted by use of the computer program without additional test runs.

The model, used to optimize the process variables so that the least amount of material is required in terms of lb/ft^2/0.010 in., predicted coating cracking and delamination of 0.76 mm (0.03 in.) thick coating. The prediction was confirmed by trial of the conditions. The model was then used to predict the least amount of material that would produce the best quality for a 1.5 mm (0.06 in.) thick coating with the least variance in desirable coating properties.

4.3 *Economy*

The amount of material required accounts for the major portion of the coating cost (i.e., assuming a coverage factor in terms of lb/ft^2/0.010 in.). The coating cost also depends to a large degree on the cost of labor and the quantity of gas used, which are proportional to the time required to produce the coating. The coating time significantly changes with powder feed rate (Fig. 2).

Figure 3 shows low powder feed rates—1.8 to 4 kg/h (4 to 9 lb/h), compared to 9 kg/h (20 lb/h)— using gas flow sets A, B, and C from Table 1. The prefix HR represents a high powder rate of 9 kg/h (20 lb/h) for conditions A, B, and C. The differences in coating coverage factors are thought to be caused by variations in deposit efficiency and coating density.

Fig. 1 Coating structure that contains the most defects

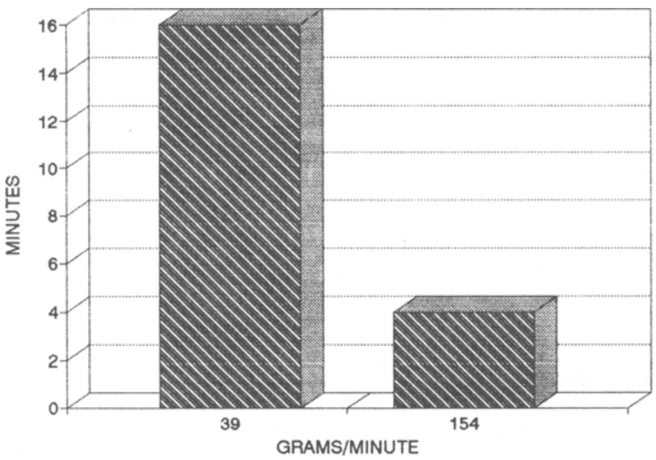

Fig. 2 Time required to deposit a coating thickness of 0.25 mm (0.01 in.) to a 0.9 m^2 (1 ft^2) area by varying the powder feed rate

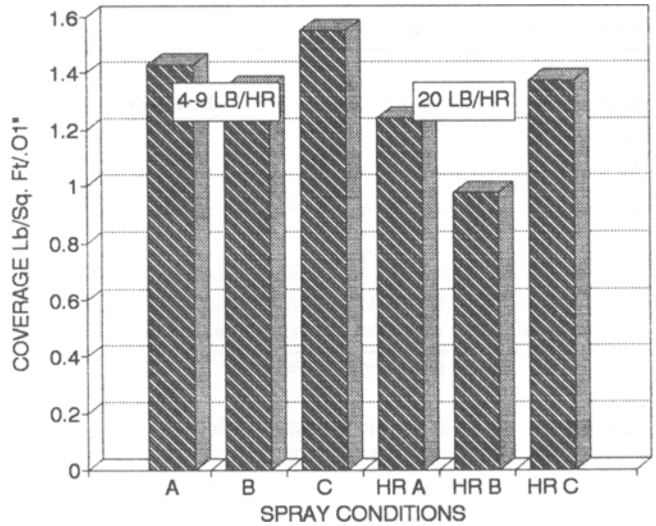

Fig. 3 Coverage factor for various spray conditions

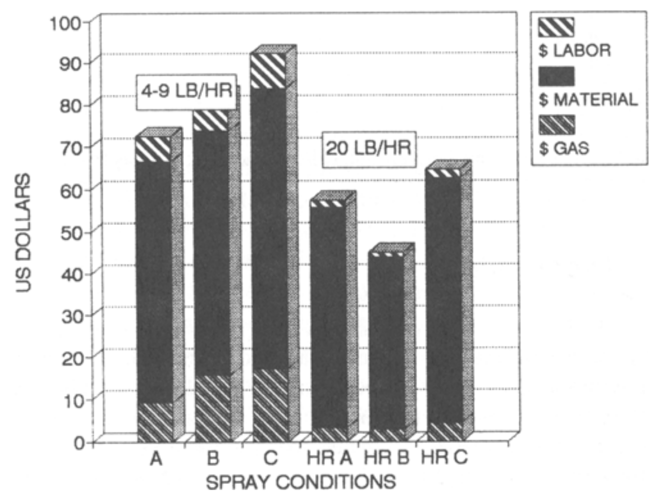

Fig. 4 Cost to deposit JK117 coating thickness of 0.25 mm (0.01 in.) thick to a 0.9 m^2 (1 ft^2) area using different process variables

Coating quality of overlays produced using conditions A and B are acceptable when applied up to 0.76 mm (0.03 in.) thick. Conditions C and HRC proved able to produce thick coatings at least to 1.3 mm (0.12 in.) when deposited on tubes. The coverage factor determined from the HRB run requires about two-thirds the amount of powder as condition C and is economically desirable.

Figure 4 shows the approximate cost to deposit a 0.25 mm (0.01 in.) thick coating to 0.09 m^2 (1 ft^2) for the conditions shown in Fig. 3. The current gas cost per hour of operation for conditions of Table 1, incurred at Stellite Coatings (Goshen, IN), are: $47.16 (Set A), $52.91 (Set B), and $62.49 (Set C). Labor cost of $30/h and the retail price for the powder in quantities of less than 23 kg (50 lb) were used for demonstrative purposes. Figure 4 does not attempt to include other factors that may affect the price of coating application such as maintenance, overhead, electricity, water, profit, setup, masking, preparation, and finishing costs.

Increasing the powder feed rate was generally found to increase the coating deposition rate proportionally. Because the coating buildup rate is faster, labor, gas, and material costs are reduced. The material cost is the largest contributor to the cost of most coatings. Reducing the amount of material required, by improving deposit efficiency, can further reduce coating costs.

The lowest coating cost shown in Fig. 4 was produced by condition HRB, followed by condition HRA. Defects such as cracks and delamination prevent use of these parameters for thick deposits. HRA conditions are impractical because of resultant spitting and nozzle loading.

4.4 *Model Predictions*

Table 3 reports the model predictions for parameter effects on coating properties. Some predictions could have been made without the designed experiment on the basis of experience, and this validates the model and final results. For example, part temperature is significantly affected by gas flow. The higher the gas flow, the hotter the part becomes, which is logical because more gas produces more heat. The model also predicts that closer

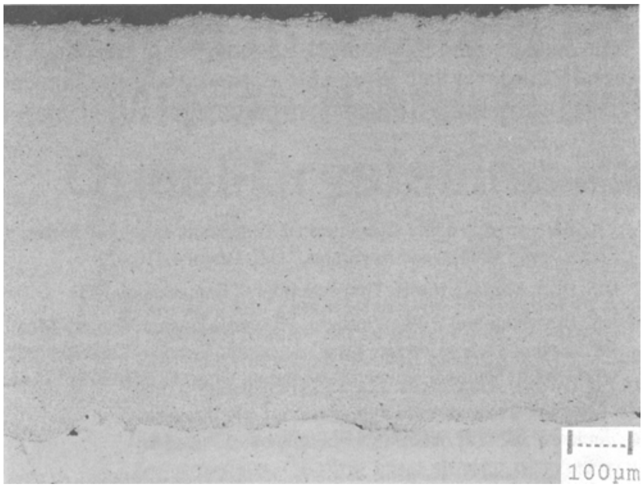

Fig. 5 JK117 produced at a spray rate of 9 kg/h (20 lb/h)

Table 5 Procedure for JK 117 high deposition rate or thickness

Variable	Part size Small	Large
Powder feed rate, kg/h (lb/h)	2.3-4.5 (5-10)	9.1 (20)
Thickness, mm (in)	>1.5 (0.06)	>1.5 (0.06)
Thickness per pass, mm (in.)	<0.025 (0 001)	0.25-0.50 (0.001-0.002)
Surface speed m/s (ft/min)	0.5-1 (100-200)	>1 (200)
Crossover per pass, mm (in.)	2-2.5 (0.08-0.1)	2.5-3 (0.1-0.12)
Spray distance, cm (in.)	18.20-200 (7-8)	18.20-200 (7-8)
Cooling(a)	Yes/No	Yes/No
Nozzle	1/4-9	1/4-9
Gas flow (Table 1)	Set C	Set C
WC insert (bore), mm (in.)	2/1.3 (0.08/0.052)	2 (0.08)

(a) If used, cooling must be stopped when spraying stops.
Note: Preheating recommended if possible. Maximum part temperature: 315 °C (600 °F). Temperature variations should be avoided during application

spray distance and higher powder feed rates increase part temperature, which is true for most thermal spray processes.

4.5 *Coating Stress*

The coatings that exhibited neutral to highly compressive stress did not exhibit delamination on flat panels. When applied to the tubes, coatings with high compressive stress exhibited crack growth as coating thickness increased. It was observed that a coating compressive stress level of less than 0.25 mm (0.01 in.) deflection did not exhibit cracking when deposited up to 3 mm (0.12 in.) thick on round surfaces and up to 1.5 mm (0.06 in.) thick on flat surfaces.

Coatings deposited with a tensile stress on the panels exceeding 0.25 mm (0.01 in.) deflection were observed to usually delaminate and occasionally crack before achieving 0.38 mm (0.015 in.) thickness. When the tensile stress was extremely high (as much as 1 mm, or 0.04 in., deflection), the coatings did not crack or delaminate on round components until the coating thickness exceeded 0.76 mm (0.03 in.).

Coating stress appears to be in tension at low flame velocities and becomes neutral as flame velocity and heat content increase. Coatings thicker than 0.76 mm (0.03 in.) produced at 2.3 kg/h (5 lb/h) powder feed rate exert significant compressive force on the substrate under set C conditions. As deposition rate and coating thickness increase, the coating becomes increasingly tensile in nature. The amount of change in stress appears to be controllable by controlling part temperature and deposition rate per pass.

The hotter the coating during deposition and the thinner the coating applied per pass, the lower the tensile stress at high deposition rates and thicknesses. Coatings of great thickness on both flats and rounds appear to favor conditions that approach neutral stress at the final coating thickness.

Table 4 shows the predicted contributions of parameter effects on cracking and delamination of the coating at two different thicknesses. The table includes data combined for both flat and round part geometry. It was observed that cracking and delamination vary due to part geometry as well as choice of coating procedure. It is possible to vary the parameters for each part shape to achieve desired coatings. However, the same parameter selection is desirable for any part geometry.

Cracking situations of rounds and flats were examined and compared. Thick coatings with highly compressive stress deposited on the tubes showed cracks, but coatings deposited on the flat panels did not.

4.6 *Part Cooling*

Air cooling has little effect on lowering part temperature at high powder feed rates and appears to be an ineffective method of part temperature control. A large volume of cold air forced onto a hot coating, especially when the gun is no longer on the part, has been observed to increase the hardness and possibly the brittleness of JK117 coatings. The high hardness of the coating, produced by rapid air cooling, may be desirable when the application requires a thin coating and when low impact strength of the coating can be tolerated. To decrease the susceptibility of hard coatings to excessive hardness or brittleness, especially when thick coating deposits are being formed, the coating and part should not be overheated during coating application and should be allowed to cool unaided.

The temperature control of large, massive parts usually is not a problem. It is a particular problem, however, when a coating is applied to small or thin parts or in a concentrated area. In this situation, short bursts of deposition, followed by a delay with the torch off the part, thereby allowing the heat from the coating to transfer to the part, assists in controlling the coating temperature.

4.7 *Optimization*

Table 5 presents the parameters and procedures that influence the overall process economics with respect to coating properties for thick deposits. The powder feed rate increases the part temperature. Therefore, it is advisable when coating small parts to reduce the powder rate to prevent the coating from becoming overheated. Coating temperatures of greater than 315 °C (600 °F) usually produce severe defects regardless of process parameters.

4.8 *Quality*

It was found that coating hardness increases and porosity decreases as the flame velocity and heat content increase. Replications of coatings up to 1.5 mm (0.06 in.) thick applied to stress panels and coatings thicker than 3 mm (0.12 in.) applied to round components consistently exhibit desirable properties while significantly reducing coating cost. Figure 5 shows the JK117 coating structure produced at a powder feed rate of 9.1 kg/h (20 lb/h) using conditions from Table 5.

5. Conclusions

The cost to produce JK117 coatings can be reduced by approximately 42% by increasing the powder feed rate and decreasing the amount of material required. The amount of material required, in lb/ft^2/0.01 in., is reduced by 13%. The time required to produce the coating at 9.1 kg/h (20 lb/h) is about one-fourth of the previous time required, which reduces gas consumption by approximately 75%. Coating quality has been shown to be improved; coatings can be successfully applied to a thickness of at least a.6 mm (0.06 in.) to flat and round surfaces with the same technique, without defects such as cracking and delamination.

Coating hardness appears to increase as coating thickness or powder feed rate increases; otherwise, the coatings are similar to those formed at lower thickness and powder rates. Coating reproduction is excellent as long as key variables, such as gas flow and part-to-gun speed, are controlled.

Coating procedures evaluated in this paper suggest strong relationships between process variables and coating properties and defects. By use of a model, reduction of coating cost and application of thick (or thin) JK117 coatings were achieved without sacrificing coating quality.

Acknowledgment

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