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Evaluating the Effects of High Velocity Oxy-Fuel (Hvof) Process Parameters on Wear Resistance of Steel-Shaft Materials

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Abstract

Thermal spray processes are widely used in industries to compensate for worn surfaces of different power transmission steel shafts. These include plain carbon, alloyed and stainless steels. This comes as a means of saving the worn parts by reusing them after they have been thermally sprayed by suitable wear-resistant coatings. As there are several factors to be controlled in this process, this makes it necessary to get the best combination of process parameters to provide the required level of wear resistance and, hence part life. In this study the oxy-fuel process is applied to 4140 alloy steel. Process parameters have been varied using a 2^k experimental design. The Pin-on-Disc test was used to estimate the wear resistance of the different material-coating-parameters combinations. The data were analyzed and a statistical model, explaining the effect(s) of different parameters as well as their interaction, was obtained.

Keywords: Statistical Modeling; Design of Experiments; High Velocity Oxy Fuel (HVOF)

1. Introduction

High velocity oxy fuel (HVOF) flame spray process is one of the most widely spread thermal spraying techniques used for the repair of worn parts such as power transmission shafts and other parts which experience continuous sliding contact [1-2]. This provides an economical and a more environmentally sound alternative for scrapping of these parts [1] and/or other coating techniques such as hard chromium plating [3-4]. A great effort has been recently devoted to investigating the HVOF process including the effect of microstructure of HVOF-sprayed coatings [5-8], in-flight particle properties [[9-11] and process parameters [8-12] on the resulting wear behaviour. In the above studies, a general trend has been observed as to the effect of in-flight particle properties on the resulting microstructure and wear resistance of the coatings; the higher the particles' velocity and temperature the denser, more coherent and more wear resistant the coating is. Studies which involved the effect of process parameters have considered several process parameters such as carrier gas flow rate [8,10], stand off distance [8-12], powder feed rate [9-10,12] and substrate surface speed [9]. These studies indicated major factors controlling the particle in-flight properties, and hence wear behaviour to be the powder feed rate and the gas flow rate, while there has been some ambiguity about the effect of stand off distance on the in-flight particle properties and the resulting wear behaviour [8,9]. This uncertainty and lack of accurate distinction of the different effect(s) of the various spraying factors may, very well, be due to their interaction effects, which have not been dealt with in the previous attempts [9]. In the light of the above a need for a more distinguishing method of analysis is obvious, i.e. a proper methodology should be able to, quantitatively; determine the effects of the various process parameters as well as their interaction effects which some times could be more prominent that the effects of separate factors themselves [13]. In this study a full factorial 2^k design of experiments (DOE) has been employed to pre-plan the experiments for further analysis of the results. Factors investigated in this study were fuel gas pressure (substitute for gas flow rate); stand off distance and rotational speed of shafts (pins) during the coating process.

2. Materials and Experimental Procedure

The substrate material used in this study was 4140 alloy steel with composition shown in Table 1. 8-mm diameter rods were prepared by turning from an original stock of 65 mm diameter for the purpose of HVOF spraying. The coating material used in this study is a commercially available iron-based coating (Eutalloy RW 19400) produced by Castolin Eutectic, Table 1. Spray parameters investigated in this study included fuel gas

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(acetylene gas) pressure; stand off distance and rotational speed of shafts (pins) during the coating process. Two levels (high and low) were used for each factor, Table 2, yielding eight different experimental combinations, Table 3. After spraying, pins were tested for wear, using the pin-on-disc test with 25 N test load and 250 rpm at 180 mm diameter. Mass loss was measured by a sensitive balance every 15 minutes with a total number of four readings recorded for each experiment. As cross sectional areas differed slightly among different specimens, mass loss data were corrected to reflect this variation and final values of mass loss per unit area were reported for analysis purposes.

Table 1. Chemical composition of substrate (4140 alloy steel) and coating material wt.%.

Material	Fe	Mn	Cr	Mo	C	Si	Ni	P
Substrate	Bal.	1	1.1	0.2	0.4	0.25	--	0.03
Coating	Bal.	0.08	16		0.26	0.9	1.87	

Table 2. Low and high values used for the different spray parameters.

Parameter (symbol)	Low	High
Acetylene gas pressure (C), Bar	3	10
Stand off distance (A), mm	100	400
Rotational speed (B), rpm	100	650

Table 3. Parameter combinations used for the different HVOF spray trials.

Experiment No.	Fuel gas pressure	Rotational speed	Stand off distance
1	High	High	High
2	High	High	Low
3	High	Low	High
4	High	Low	Low
5	Low	High	High
6	Low	High	Low
7	Low	Low	High
8	Low	Low	Low

3. Results and Discussion

The designed experiments were performed and the output of each experiment was recorded as a mass-loss (to be considered as response) as shown in Table 4.

The results, qualitatively, indicate the following general trends (i) mass loss decreased with increasing gas pressure; (ii) at the same pressure- level-rotational-speed combination, the mass loss decreased with increasing the stand off distance with this effect being more evident at high pressure levels, indicating a stronger interaction and (iii) rotational speed does not seem to have a large impact on the average mass loss.

These experiments were analysed, Figure 1, and a statistical model was obtained, (1). Figure 1 shows the half normal probability plot of the effects' estimates for the above experiments. This is a plot of the absolute value of the effect estimates against their cumulative normal probabilities. Many analysts feel that the half-normal plot is easier to interpret, particularly when there are only a few effect estimates such as when the experimenter has used an eight-run design similar to the case in this paper.

Table 4. Parameter combinations used for the different HVOF spray trials and their respective average mass loss (mg/mm^2).

Experiment No.	A Distance mm	B R. Speed rpm	C Pressure Bar	Response Av. Mass loss mg/mm^2
1	400	650	10	0.008
5	100	650	10	0.027
3	400	100	10	0.010
7	100	100	10	0.045
2	400	650	3	0.033
6	100	650	3	0.039
4	400	100	3	0.051
8	100	100	3	0.037

The important effects that emerge from this analysis (indicated by their large distance from the straight line) are the gas pressure (C), the stand off distance (A) and the interaction between these two factors (AC). The rotational speed, however, does not have the same level of effect. The acetylene gas pressure in the model (1), also appears to be the dominant factor in the average loss of mass model, followed by the interaction effect between gas pressure and stand off distance and then by the stand off distance as a separate factor.

Figure 1 and the statistical model (eqn. 1) also show an effect of the three-factor interaction, (ABC) on the average mass loss. This ABC interaction has more effect on the average mass loss than the rotational speed factor alone, indicating the fact that interaction effects could exceed the effects of some principal process parameters.

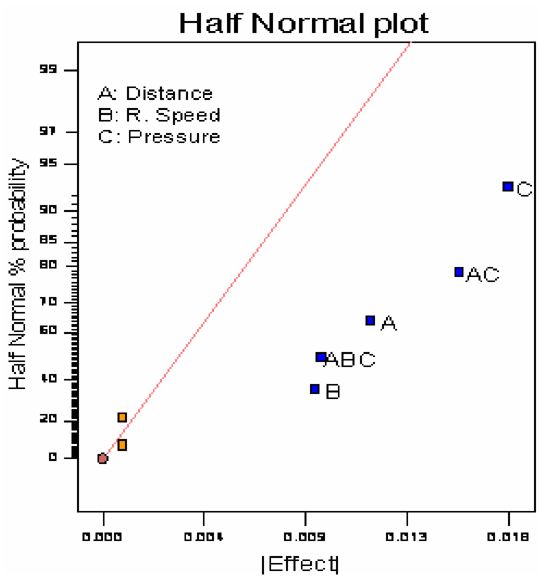

Figure 1. Effects of different factors on the average mass loss.

$$Av.\ Loss = +0.031 - 0.0058*A - 0.0046*B - 0.0086*C - 0.0077*AC + 0.0048*ABC \quad (1)$$

To check the adequacy of the model above, normality assumption should be checked. Residual analysis is an efficient and major tool used in this diagnostic checking. The model is tested against normality of its residuals, Figure 2, indicating no presence for any outliers nor indication of non-normality. The general impression from examining this figure is that the error is approximately normal. The tendency of the normal probability plot to bend down slightly on the left side and upward slightly on the right side implies that the tails of the error distribution are somewhat thinner than would be anticipated in normal distribution.

The experiments were performed randomly, and in order to check the independence assumption, plotting the residuals in time order of the data was performed as shown in Figure 3. A tendency to have runs of positive and negative residuals indicates positive correlation. Figure 3, shows no correlation between residuals.

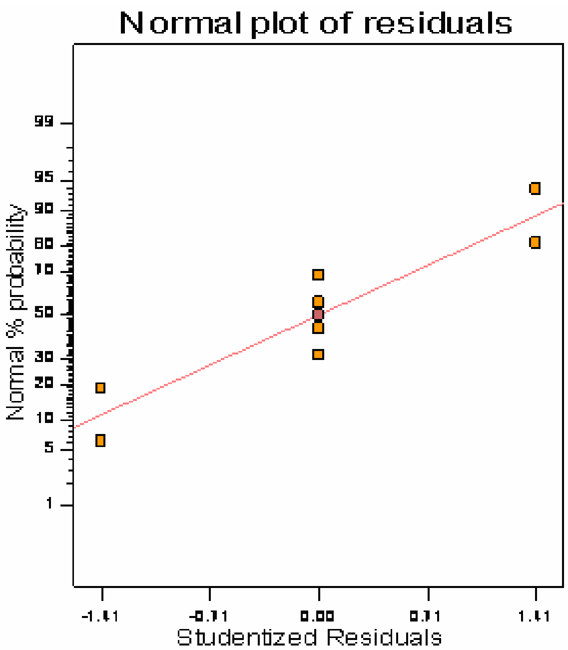

Figure 2. Normal Plot of Residuals.

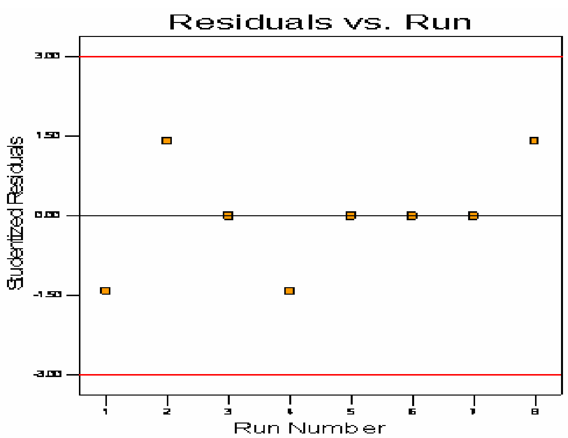

Figure 3. Plot of residuals versus run order or time.

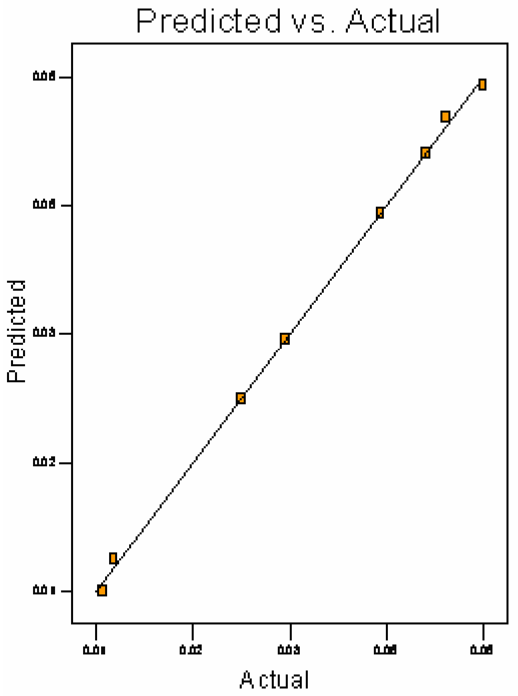

Figure 4. Plot of actual versus predicted values.

Another test on the prediction model is comparing the actual values against their corresponding predicted values obtained from the model. Figure 4, provides a clear picture of the negligible differences between the predicted values and the actual ones indicating adequacy of the obtained statistical model.

The analysis of variance (ANOVA) for the selected factorial model, Table 5, was significant with p-value = 0.0044, against F-value of 225. There is only a 0.44% chance that a "Model F-Value" this large could occur due to noise. Also it is evident from the ANOVA that all the model terms were significant .

As mentioned above, the two-factor-interaction effect between the acetylene pressure and the stand off distance (AC) had more prominent effect than the rotational speed factor. This interaction effect is evident in Figure 5, where greater mass losses are favored by a low gas pressure and a high stand off distance.

When the level of the gas pressure is high and the stand off distance level is high, then the average mass loss is the minimum. While, if the level of the gas pressure is low and the stand off distance level is high, the average mass loss is high.

4. Conclusion

Wear resistance of HVOF coating (represented by mass loss) is affected by the respective process parameters such as, fuel gas pressure (flow rate), stand off distance and speed. In this study a statistical model was developed covering all the above factors in one equation. It is clear that the effect of the gas pressure seems to be the greatest, followed by the interaction between the gas pressure and the stand off distance. The rotational speed did not show a significant level of effect on the average mass loss. The model adequacy seems to be high, as excellent agreement between experimental and predicted values has been observed.

Table 5. Analysis of variance for the statistical model.

ANOVA for Selected Factorial Model					
	Sum of		Mean	F	
Source	Squares	DF	Squares	Value	Prob. > F
Model	1.72E-03	5	3.45E-04	225.13	0.0044
A	2.7E-04	1	2.7E-04	176.51	0.0056
B	1.71E-04	1	1.71E-04	111.76	0.0088
C	6.21E-04	1	6.21E-04	405.73	0.0025
AC	4.81E-04	1	4.81E-04	313.80	0.0032
ABC	1.81E-04	1	1.81E-04	117.88	0.0084
Residual	3.06E-06	2	1.53E-06		
Total	1.73E-03	7			

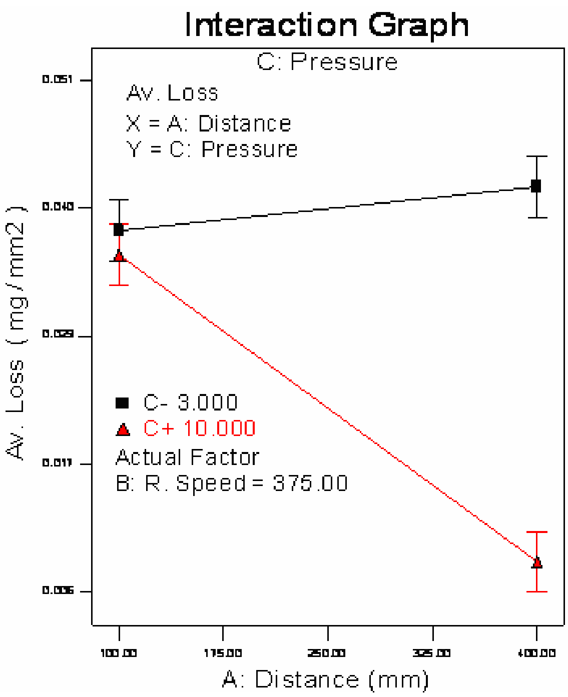

Figure 5. Pressure-Distance interaction effect on average mass loss.

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