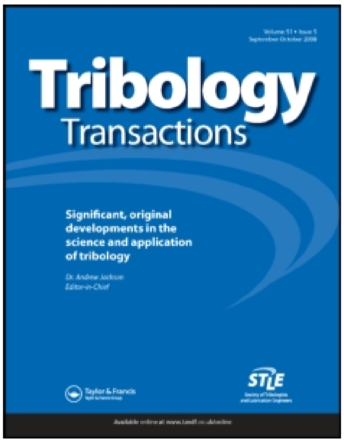

Tribology Transactions
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713669620

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First Published on: 01 May 2009

To cite this Article Mishra, S. C., Das, Satyabati, Satapathy, Alok, Ananthapadmanabhan, P. V. and Sreekumar, K. P.(2009)'Erosion Wear Analysis of Plasma Sprayed Ceramic Coating Using the Taguchi Technique',Tribology Transactions,52:3,401 — 404

To link to this Article: DOI: 10.1080/10402000802687874

URL: http://dx.doi.org/10.1080/10402000802687874

Tribology Transactions, 52: 401-404, 2009

ISSN: 1040-2004 print / 1547-397X online
DOI: 10.1080/10402000802687874

STLE
Society of Tribologists and Lubrication Engineers

Erosion Wear Analysis of Plasma Sprayed Ceramic Coating Using the Taguchi Technique

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Erosion wear behavior of fly ash–illmenite coating was studied using dry silica sand as an erodent. A plan of experiments based on the Taguchi technique was used to acquire the data in a controlled way. An orthogonal array and signal-to-noise ratio was employed to investigate the influence of the impact angle, the velocity, the size of the erodent, and the standoff distance (SOD) on erosion wear. The objective was to investigate which design parameter significantly affects the erosion wear. It was found that the impact angle is the most powerful factor influencing the erosion wear rate of the coating. Further, when erosive wear behavior of fly ash–illmenite coating was investigated at three impact angles (i.e., at 30°, 60°, 90°), it was revealed that the impact angle is the prime factor and maximum erosion takes place at $\alpha = 90°$.

KEY WORDS

Ceramic Coating; Erosion Wear; Taguchi Technique

INTRODUCTION

Solid particle erosion is a wear process where particles strike against a surface and promote material loss. During flight, a particle carries momentum and kinetic energy, which can be dissipated during impact due to its interaction with a target surface (Roberto, et al. *(1)*). Erosion is a nonlinear process with respect to its variables, either materials or operating conditions. To obtain the best functional output of coatings exhibiting selected in-service properties, the right combinations of operating parameters need to be known. These combinations normally differ by their influence on the erosion wear rate; i.e., coating mass loss. A lower erosion wear rate is one of the main requirements of coatings applied by plasma spraying. In order to achieve certain values of the erosion rate accurately and repeatedly, the influencing parameters of the process have to be controlled accordingly. Since the number of such parameters is too large and the parameter-property correlations are not always known, statistical methods can be employed for precise identification of significant control parameters for optimization. In recent years, the Taguchi method has become a widely accepted methodology for improving productivity. This method consists of a plan of a minimal number of experiments with the objective of acquiring data in a controlled way, executing these experiments, and analyzing data, in order to obtain information about the behavior of a given process. One of the advantages of the Taguchi method over the conventional experiment design methods is that it minimizes the variability around the target when bringing the performance value to the target value in addition to keeping the experimental cost at the minimum level. Another advantage is that optimum working conditions determined from the laboratory work can also be reproduced in the real production environment (Sahin *(2)*). Precisely, Taguchi's design is a simple, efficient, and systematic approach to optimize designs for performance, quality, and cost (Prasad, et al. *(3)*; Chua, et al. *(4)*; Taguchi *(5)*; Yang and Tarn *(6)*; Phadke *(7)*). Hence, in this work, the Taguchi experimental design method was adopted to investigate the effects of the impact angle, the velocity, the size of the erodent, and the standoff distance on the erosion wear rate of fly ash–illmenite coatings.

Manuscript received May 19, 2008
Manuscript accepted November 26, 2008
Review led by Emmanuel Ezugwu

EXPERIMENTAL

A standard Taguchi experimental plan with notation L9 was chosen as outlined in Table 1 and the erosion wear rates were obtained by carrying out experiments under such conditions for fly ash–illmenite coatings made at 15 and 11 kW power levels (Das *(8)*).

The coating made at 15 kW power level is eroded at different impact angles (i.e., at 30°, 60°, 90° angle) with the standoff distance of 150 mm at an impact velocity of 58 m/s with the average erodent particles size of ∼400 μm. Dry silica sand is used as the erodent and the experiments were carried out at room temperature (27°C) with relative humidity of 30%. Amount of wear was determined on a "mass loss" basis (Nicholls, et al. *(9)*; Mishra, et al. *(10)*). It is done by measuring the weight change of the samples at regular time intervals during the test duration. A precision electronic balance with 0.001 mg accuracy was used for weighing. Erosion rate, defined as the coating mass loss per unit erodent mass (gm/gm), was calculated.

RESULTS AND DISCUSSION

Figure 1 shows that the erosion wear rate of coatings under different test conditions, as obtained in Table 1, were almost the

TABLE 1—EXPERIMENTAL LAYOUT AND EROSION WEAR RATE UNDER DIFFERENT TEST CONDITIONS FOR COATINGS AT 11 KW AND 18 KW POWER LEVELS

Sl. No (Test runs)	A Erodent size (micron)	B Angle of Impact (degree)	C Impact Velocity (m/s)	D Stand-off Distance (mm)	Er (mg/kg) 11 kW	Er (mg/kg) 18 kW
1	300	30	32	120	65.64	67.564
2	300	60	44	160	91.73	94.573
3	300	90	58	200	92.45	96.475
4	500	30	44	200	73.4	67.5
5	500	60	58	120	170.9	176
6	500	90	32	160	129.1	136.463
7	800	30	58	160	80.9	77.765
8	800	60	32	200	111.79	116.4
9	800	90	44	120	148.82	144.5

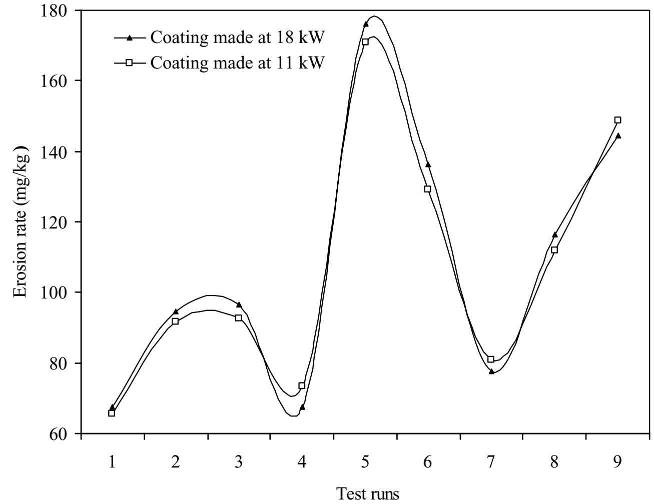

Fig. 1—Erosion wear rate of coatings under different test conditions.

same. To obtain optimal parameters, the lower-the-better quality characteristic for the erosion wear rate was chosen. An analysis of the influence of each control factor on the coating efficiency was made with the signal-to-noise (S/N) ratio that measures the quality characteristics deviating from or near the desired values using MINITAB computer software package. The S/N ratios for coating erosion wear rate at 11 and 18 kW are shown in Table 2. The influence of the interactions between the control factors was also analyzed in the response table. The control factor with the strongest influence was determined by the differences of the obtained values. The higher the difference, the more influential the control factor or an interaction of two controls. The S/N response graph for coating erosion wear rate is shown in Figs. 2 and 3.

It is interesting to note that the Taguchi experimental design method identified the impact angle and the size of the erodent as the most powerful factor influencing the erosion wear rate of the fly ash–illmenite coatings. At the standoff distance, the velocity of impact emerged as the other significant factor affecting the coating erosion wear rate. The impact angle thus is the significant process variable.

Based on the above findings, erosion wear was carried out at a different angle of impact of the solid particle erosion on the coating made at 15 kW power level for 20 min. The variation of cumulative mass loss with time in the case of the coating deposited at 15 kW is illustrated in Fig. 4.

It is seen that the coating mass loss increases with increasing time of attack. The cumulative increment in material loss due to the erosion wear of plasma-sprayed coatings with time and the erodent dose has been studied by Levy *(11)*. In the present work such a trend is also found, subjected to the erosion test irrespective of the angle of impact. Figure 5 shows the variation of erosion rate with time, with 400 μm size erodent, at impact angles of 30°, 60°, and 90°, at SOD of 150 mm and at pressure of 6.5 kgf/cm^2 (impact velocity of 58 m/s) for the sample coated at 15 kW power level.

From Fig. 5 it is observed that the erosion rate increases and then decreases with time. This can be attributed to the fact that the fine protrusions on the top layer of the coatings may be relatively loose (i.e., interparticle bonding may be less strong) and removed with less energy than what would be necessary to remove a similar portion/layer from the bulk of the remaining layers in the coating further in time. Consequently, the initial wear rate is high. With increasing exposure time the wear rate starts decreasing and in the transient regime, a steady-state wear rate is approached.

It is also observed that the erosion rate increases with increasing angle of impact and maximum erosion takes place at $\alpha = 90°$. Alahelisten, et al. *(12)* have studied the erosion wear rate for

TABLE 2—S/N RATIOS FOR COATING EROSION WEAR RATE AT 11 KW AND 18 KW

Sl. No (Test runs)	A Erodent Size (micron)	B Angle of Impact (degree)	C Impact Velocity (m/s)	D Stand-off Distance (mm)	Er (mg/kg) 11 kW	S/N Ratio	Er (mg/kg) 18 kW	S/N Ratio
1	300	30	32	120	65.64	−36.3434	67.564	−36.5943
2	300	60	44	160	91.73	−39.2502	94.573	−39.515
3	300	90	58	200	92.45	−39.3181	96.475	−39.6883
4	500	30	44	200	73.4	−37.3139	67.5	−36.5861
5	500	60	58	120	170.9	−44.6548	176	−44.9103
6	500	90	32	160	129.1	−42.2185	136.463	−42.7003
7	800	30	58	160	80.9	−38.159	77.765	−37.8157
8	800	60	32	200	111.79	−40.9681	116.4	−41.3191
9	800	90	44	120	148.82	−43.4538	144.5	−43.1974

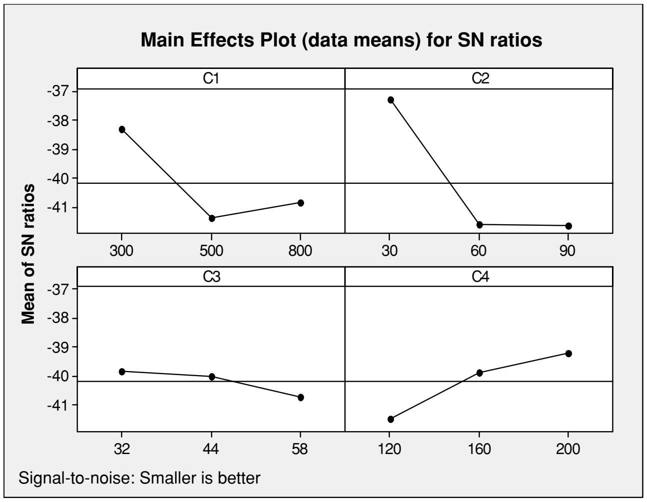

Fig. 2—Relative effect of main factors on erosion rate of the coatings made at 11 kW.

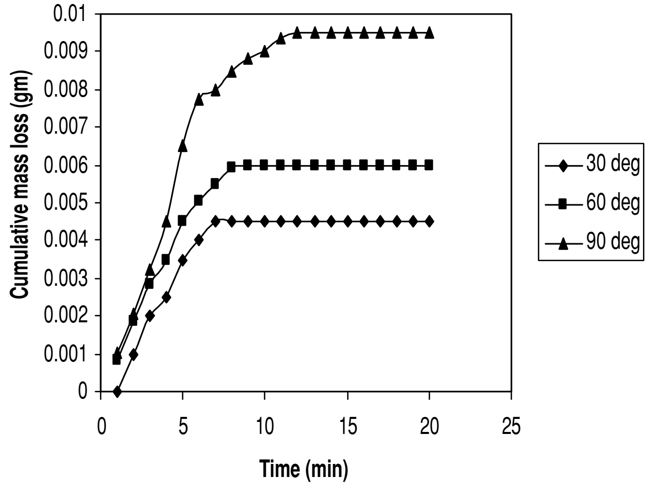

Fig. 4—Variation of coating mass loss with time, for 400 μm size erodent, SOD of 150 mm and at impact velocity of 58 m/s.

diamond coating and obtained the maximum erosion at 90° impact angle and an increase of the erosion rate with an increase in pressure of the erodent as well. This is typical of all brittle coatings. The relationship between the erosion rate E and the impact angle (α) as suggested by Bayer *(13)* is

$$E = (K_d v^n Cos^n \alpha + K_b v^m Sin^m \alpha)M$$

For a particular test condition, the velocity of impact v and the erodent supply rate M are constant. The constants K_d, K_b, m, n are determined by fitting the equation to experimental data. For typical brittle materials $K_d = 0$ and the erosion rate is maximum at a 90° impact angle. For typical ductile material, $K_b = 0$ and the erosion rate is largest between 20° and 30° impact angles.

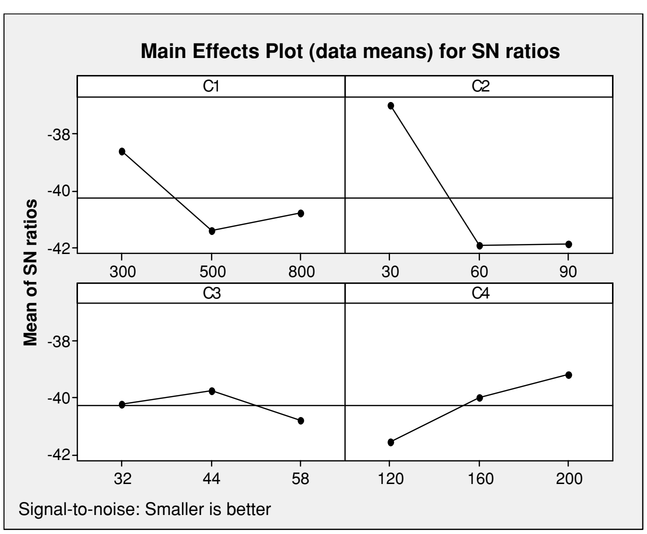

Fig. 3—Relative effect of main factors on erosion rate of the coatings made at 18 kW.

This variation of erosion wear loss confirms that the angle at which the stream of solid particles impinges the coating surface influences the rate at which the material is removed. It further suggests that this dependency is also influenced by the nature of the coating material (Das *(8)*). The angle of impact determines the relative magnitude of the two components of the impact velocity, namely, the component normal to the surface and the one parallel to the surface. The normal component is responsible for the lasting time of impact (i.e., contact time) and the load. The product of this contact time and the tangential (parallel) velocity component determines the amount of sliding that takes place. The tangential velocity component also provides a shear loading to the surface, which is in addition to the normal load of the normal velocity component. Hence, as this angle changes, the amount of sliding that takes place also changes, as does the nature and the magnitude of the stress system. Both of these aspects influence the way a coating wears. These changes imply that different types of material would exhibit different angular dependencies.

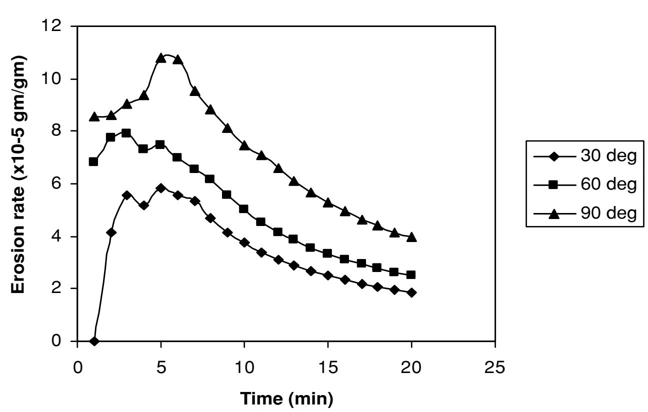

Fig. 5—Variation of erosion rate with time for the sample coated at 15 kW power level.

CONCLUSIONS

From the Taguchi experimental design method the impact angle was identified as the most powerful factor influencing the erosion wear rate of the fly ash–illmenite coatings. Further, this investigation revealed that the erosion rate increases with increasing angle of impact and the maximum erosion takes place at $\alpha = 90^\circ$. Initially the wear rate increases sharply with the time of impact and after a few minutes the erosion rate becomes lower in magnitude and finally reaches a steady state.

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