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EVALUATION OF EROSION WEAR OF A CERAMIC COATING WITH TAGUCHI APPROACH

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ABSTRACT

Solid particle erosion is a complex surface damage process influenced by a number of control parameters that collectively determine the erosion rate. The present piece of work investigates the significant process parameters which affect the solid particle erosion wear behaviour of fly ash – quartz coatings, using Taguchi analysis technique. It is found that the impact angle is the most powerful influencing factor for the erosion wear of the coatings. Further, when erosive wear behavior of the coating was investigated at three impact angles (i.e. at 30^0, 60^0, 90^0), revealed that maximum erosion takes place at 90^0 impact angle.

Keywords: *Fly ash, quartz, erosion wear, Taguchi technique.*

1. INTRODUCTION:

In a wide variety of applications, mechanical components have to operate under severe conditions such as in helicopter rotor blades; pump impeller blades; high speed vehicles; coal and biomass fired boiler tubes and turbines blades and vanes operating in desert environments etc., where they are subjected to solid particle erosion. Thus surface modification is necessary to protect them against various types of degradation. Ceramic coatings produced by plasma spray technique are widely used for a range of industrial applications to confer erosion wear resistance [1]. Due to operational requirements in dusty environments, study of erosion characteristics of these ceramic coatings is of high relevance [2].

Solid particle erosion is a dynamic process that leads to progressive loss of material from the target surface due to impingement of fast moving solid particles [3]. During flight, a particle carries momentum and kinetic energy, which is dissipated during impact at target surface [4]. Erosion is a non-linear process with respect to its variables, either materials or operating conditions. The erosion of ceramic coatings may be influenced by both coating properties and impacting particle conditions including its size, velocity, impact angle etc. [2]. To obtain the best functional output of coatings exhibiting selected in-service properties, the right combinations of operating parameters are to be known. These combinations normally differ by their influence on the erosion wear rate i.e. coating mass loss. The less erosion wear rate is the main requirements of the coatings developed by plasma spraying. In order to achieve certain values of 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 process optimization. In recent years, Taguchi method has become a widely accepted methodology for improving productivity [5]. This method consists of a plan 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 be also reproduced in the real production environment [6]. Precisely, Taguchi's design is a simple, efficient and systematic approach to optimize designs for performance, quality and cost [5, 7-10]. Hence, in this work, Taguchi experimental design method was adopted to investigate the effects of impact angle, velocity, size of the erodent and stand off distance on erosion wear rate of fly ash-quartz coatings.

2. Experimental

Plasma spray coating of fly ash-40%quartz is deposited on metal substrates using atmospheric

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plasma spray system. The operating parameters during the coating deposition are given in Table 1.

Table 1. Operating parameters of the plasma spray unit

Operating Parameters	Values
Plasma Arc Current (amp)	400
Arc Voltage (volt)	45
Plasma Gas (Argon) Flow Rate (Lpm)	28
Secondary Gas (N2) Flow Rate (Lpm)	3
Carrier Gas (Argon) Flow Rate (Lpm)	12
Powder Feed Rate (gm/min)	15
Torch to Base Distance TBD(mm)	100

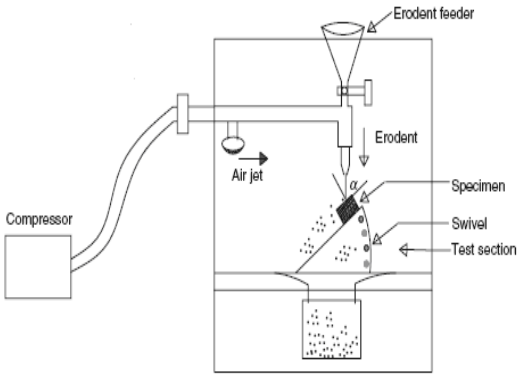

Figure 1. A schematic diagram of erosion test rig

Dry silica sand of different particle sizes (150, 260 and 360 µm) were used as erodent. The velocity of the eroding particles was determined using standard double disc method [11]. Coatings were eroded with silica sand at different impact angles (i.e. at 30^0, 60^0, 90^0). Amount of wear was determined on 'mass loss' basis [12, 13]. It was 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 (mg/kg) was calculated. A standard Taguchi experimental plan with notation **L9** was chosen [14], and the operating parameters under which erosion tests were carried out are shown in table 2 The exhaustive literature review on erosion behavior of brittle ceramic materials reveals the effect of the various parameters which largely affect the erosion rate of coatings [15]. In conventional experimental design, it would require 3^4 = 81 runs to study four parameters each at three levels, whereas Taguchi's experimental approach reduces it to only 27 runs, offering a great advantage in terms of experimental time and cost. The experimental observations are further transformed into signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of performance characteristics. The S/N ratio for minimum erosion rate can be expressed as ''lower is better'' characteristic, which is calculated as logarithmic transformation of loss function as per equation 1.

Table 2. Levels of variables used in the experiment

	Levels			
Control factors	**I**	**II**	**III**	**Units**
A: Erodant size	150	260	360	µm
B: Impingement angle	30	60	90	Degrees
C: Velocity of impact	32	44	58	m/sec
D: Stand off distance	100	140	180	mm

Smaller is better characteristic:

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \qquad \text{---------- (1)}$$

where 'n' the number of observations, and y the observed data. The ''lower is better (LB)'' characteristic, with the above S/N ratio transformation, is suitable for minimization of erosion rate.

3. Results and Discussion

The erosion wear rates (of the coating) at different test conditions and the signal-to-noise ratios (S/N) so obtained according to Taguchi experimental design are given in table 3.

To obtain optimal parameters, the lower-the-better quality characteristic for erosion wear rate was chosen. Analysis of the influence of each control factor on the coating efficiency was made with signal-to-noise (S/N) ratio that measures the quality characteristics deviating from or nearing to the desired values, using **MINITAB 14** software package. The

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control factor with the strongest influence was determined by differences of the obtained values. The higher the difference, the more influential is the control factor or an interaction of two controls. The S/N response for erosion wear rate is presented in table 4 and shown in fig. 2

Table 3. S/N ratios for coating erosion wear rate at 18kW

Test runs	A	B	C	D	Erosion wear rate (mg/kg)	S/N Ratio
1	150	30	32	100	238.095	-47.5350
2	150	60	44	140	243.055	-47.7141
3	150	90	58	180	317.460	-50.0338
4	260	30	44	180	166.667	-44.4370
5	260	60	58	100	283.018	-49.0363
6	260	90	32	140	238.095	-47.5350
7	360	30	58	140	172.413	-44.7314
8	360	60	32	180	185.185	-45.3521
9	360	90	44	100	253.396	-48.0760

Table 4 Signal to noise ratio (S/N) response table for erosion rate

Level	A	B	C	D
I	-48.43	-45.57	-46.81	-48.22
II	-47.00	-47.37	-46.74	-46.66
III	-46.05	-48.55	-47.93	-46.61
Delta	2.37	2.98	1.19	1.61
Rank	2	1	4	3

Analysis of the result leads to the conclusion that factor combination of A_{III}, B_I, C_I and D_{III} gives minimum erosion rate. Table 4 shows that, as far as the minimization of erosion rate is concerned; factors A, B, D play the major role. From this response table, it can be concluded that, among all the factors impingement angle is most significant followed by erodent size and stand off distance; on the erosion wear behavior of plasma sprayed coatings considered in the present investigation. Thus, the impingement angle can be taken as the significant process variable influencing the erosion wear rate of fly ash quartz coatings (as the signal to noise ratio is minimum).

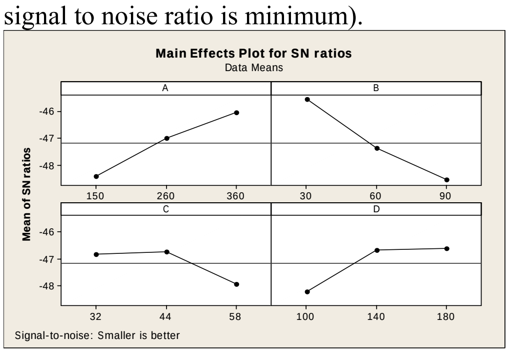

Figure 2. Relative effect of main factors on erosion rate of the coatings made at 18kW.

Erosion wear tests are carried out at different impact angles (on the coating made at 18kW power level). The variation of cumulative mass loss with time is illustrated in fig 3

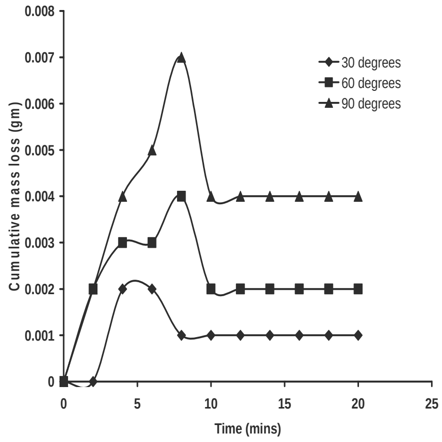

Figure 3. Variation of Coating mass loss with time, for 150µm size erodent, SOD of 100 mm and at impact velocity of 58m/sec.

It is observed that coating mass loss increases with increasing the time of attack. But after a certain time the cumulative mass loss takes a decreasing trend. Finnie has explained that such type of situation i.e. drastic drop of erosion rates is due to transition from brittle to ductile behaviour [15]. Sparks and Hucthings [16] have also discussed this type of transition in detail

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using models based on Hertzian fracture and lateral fracture. And such mechanisms are explained in the book edited by Ritter [17].

Fig 4. shows the variation of erosion rate at impact angles of 30^0, 60^0, 90^0; at standoff distance of 100mm and at a pressure of 6 MPa (velocity ≈ 58 m/s). From the figure it is observed that, the erosion rate decreases with time irrespective of the angle of impact. Such observation was also mentioned by L.Rama Krishna et.al. that the rate of erosion decreased with time for longer exposure [18]. Such type of behaviour has also been noted by Mishra et.al. [14]. This can be attributed to the fact that, the fine protrusions on the top layer of the coatings is removed with less energy i.e. at initial attack by erodent and also the surface get strain hardened, so higher energy/time of attack is needed to remove a similar portion/layer from the bulk of the remaining layers of the coating at further time length. Consequently, the initial wear rate is high. With increasing erosion time, the wear rate starts decreasing and in the transient regime, a steady state is obtained

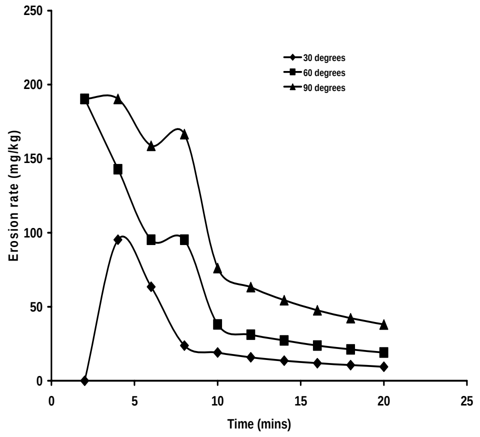


Figure 4. Variation of erosion rate with time for the sample coated at 18 kW power level.

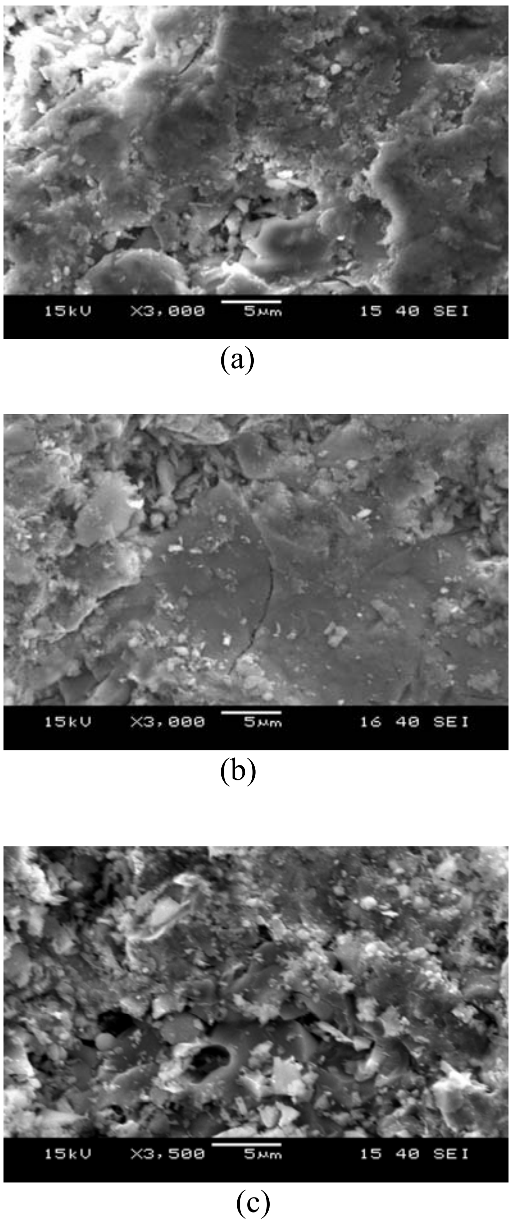
It is also observed that, the erosion rate increases with increasing the angle of impact and maximum erosion takes place at α = 90^0. Alahelisten [19] has studied erosion wear rate for diamond coating and obtained the maximum erosion at 90^0 impact angle, and increase of erosion rate with increase in pressure of the erodent too. This is typical of all brittle coatings. The relationship between erosion rate (E) and impact angle (α), as suggested by Bayer [20] using equation 2 is,

$$\mathbf{E = (K_d\, v^n\, Cos^n\alpha + K_b\, v^m\, Sin^m\alpha)\, M \quad --- (2)}$$

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

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. The angle of impact determines the relative magnitude of the two components of the impact velocity namely, the component normal to the surface and parallel to the surface. The normal component may be responsible for the lasting time of impact (i.e. contact time) and the velocity of impingement. 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, 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 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 dependency.

Surface morphology of fly ash-quartz coating after being eroded for 20 minutes at different impact angle are shown in fig.5. Fig. 5(a) shows the surface morphology of worn surface when the erodent is impacted at 30^0. Chipping away of layers/plowing caused by shear component of erodent particles might be playing the principal role and hence more cavities are formed. Some small cracks are observed and spread along grains/splats boundaries. At 90^0 angle of impact, fig.5(c), sharp deep groves are seen which is due to dominating effect of perpendicular component of the force of impingement of the erodent. As described by Maozhong [21], during normal impacting of the erodent particles, the surface of the coating endures Hertz force; partial plastic deformation takes place and cracks initiate. The cracks propagate through the grain boundaries. And then the flattened grains on the coating surface loose and eventually fall off by repeated impact. Fig. 5(b) exhibit the morphology of worn surface when erodent is impacted at 60^0. It is clearly seen that the traces of chipping/plowing are not as shallow and flat as was at 30^0 and/or 90^0 impact angle. So, erosion at 60^0 is somewhere in between that at 30^0 and 90^0 impingement angle



(a)

(b)

(c)

Figure 5. SEM Micrograph of eroded surfaces at angle of impact (a) 30^0 (b) 60^0 (c) 90^0 with sand as erodent

4. Conclusions

From the Taguchi experimental design, impact angle is identified to be the most significant factor influencing the erosion wear of fly ash-quartz coatings. Further, this investigation reveals that maximum erosion takes place at the impact angle of 90^0. Initially the wear rate increases sharply with time, and then it lowers and finally reaches a steady state irrespective of the angle of impact. The SEM Micrograph showing the surface morphology of eroded surfaces unfolds the mechanism of erosion wear at various angles of impact. Erosion wear at 90^0 impact angle involves the abrasive particles impact extruding the surface of the coatings to produce indentations and extruded lips. The lips become work hardened by repeated impact of the particles and eventually fall-off. Whereas when erodent impact at acute angles erosion wear is dominated due to micro cutting, plowing and tunneling via pores and inter particle/grain boundaries

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