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Analysis of Erosive Damage of Low Carbon Steel Using Taguchi Method

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Abstract*-The erosion characteristics of low carbon steel have been evaluated practically at a variety of test parameters using dry compressed air jet test rig under ambient temperature. A symmetrical silica sand (SiO_2) is taken in to account as erodent within range of 300-600 μm. The impact velocity within 30-50 m/sec, impact angle 15-90 ° and stand-off distance 15-25 mm are inspected as other relevant operating test conditions. The test results are designated using Taguchi's concept to ensure the minimization of observations for clarification of results in alternative process. ANOVA data analysis is considered to signify the interaction of tested parameters as well as identifying most influencing operating parameter. S/N ratio indicates that there is 0.726 % deviations are estimated between predicted and experimental results.*

Keywords: Low carbon steel, erosion rate, operating parameters, analyzing methods, ANOVA

1. INTRODUCTION

Erosion is described as the progressive loss of original material from a solid surface due to mechanical interaction between the surfaces and impinge solid or liquid particle which may be a multi-component fluid or impinging solid or liquid particles also. Erosive damages of different materials in modern technological systems are very concerning issue for sustainability of the materials with these adverse conditions. In advanced engineering and industrial field, light weight of materials has several applications for minimizing the operating as well as initial investment cost. In different environmental conditions, wind turbine, blower fan blade, hydraulic turbine impellers, the moving components of ship, aircraft, train and automobile structure made by different metals and alloys experiences the difficulty of impingement of solid particles in the form of erosion. Low carbon steel can be used extensively in erosive wear environment for its simple manufacturing technique, suitability to design different systems and mechanisms and lower manufacturing cost. Concerning these facts, the low carbon steel has been chosen as test samples to examine the erosion resistance at different operating conditions so that the exact nature of erosion can be identified.

The researches have been done by the different tribology research groups [1-6] realized that erosive wear of materials related with the various factors such as impingement angle, impact velocity, particle size, particle shape, particle type, particle flux, temperature, nozzle geometry, type of materials, hardness of the materials, stand-off distance, test duration, roughness of the tested materials etc. Among these factors impingement angle and impact velocity have been recognized as two parameters that noticeably influence the erosion rates of different materials [2]. The erosive behavior of AISI 440C stainless steel and a cermet has been conducted by researchers[7] observed that Both of the materials exhibited noticeable plasticity during impact conditions, but in case of stainless steels which has been characterized more ductile in nature. The blending conditions of materials, temperature, pressure, and flow can create the erosive-corrosive wear especially for metal and alloys [8]. Rather than different mechanical properties and operating conditions material hardness has certain amount of role to propagate erosion damage throughout the metals and alloys [9]

The previous works [1-6] on metal and alloys varying with different operating and processing conditions as well as mechanical properties and varying percentage of material-combinations on erosion of materials cannot suggest any unique trends of the results. Therefore, the objective of this work is to investigate the erosive wear performance of low carbon steel under several test conditions to understanding the possible nature of erosion. A theoretical model for estimation of erosion wear rate under multiple impact conditions and correlation of erosion rate with U. NO and friction co-efficient are developed. To analyze the obtained results in board concept, Taguchi, ANOVA and erosion efficiency, approach has been discussed

2. Experimental details

2.1Materials properties, preparation and method of erosion measurement

The measured mechanical properties of tested of low carbon steel are listed in Table 1. Rectangle type specimens with a size of 50mm×30mm×5mm were prepared by utilizing a diamond cutter from injection moulded plaques. Before the erosive wear tests all specimens were cleaned with acetone. Great care was given to ensure clean surface before and after wear tests. Sand and dust particles were cleaned after erosion test with air blasting and then balanced carefully.

Different grain size (300-355, 355-500, 500-600 microns) with irregular shaped (combination of rounded, slightly rounded and angular) dry quartz type silica sand (hardness: 42, 43.2 and 44 MPa, density 1436, 1440 and 1443 kg/m^3) of chemical composition SiO_2 was used as an erodent particle. Motor type vibration sieve machine (model: VSS-T, Vinsyst Technologist, ISO 900, India) with measuring range 97µm to 4mm was used to measure the particle size.

The weight of the samples before and after erosion process was measured by using precision digital electronic balance (model: SP404D, Sciencetech Inc, USA). Erosion rates were calculated from the differences of weight loss by considering unit of time $\left(E_R = \frac{W_{before}-W_{after}}{Time}\right)$.

Table 1: Mechanical and related properties of low carbon steel

Property	Standard Value (S.I.)	Actual or measured data	Units (S.I.)
Density	7.87	7.85	gm/cc
Tensile yield Strength	295	293	MPa
Modulus of elasticity	200	198	GPa
Poisson's Ratio	0.29	0.29	
Ultimate Tensile Strength	394	391	MPa
Hardness	115	111	Brinell

2.2 Test apparatus

A sand blast erosive wear testing device was designed and fabricated to understand the erosion process, as shown in Figure 1.In this sand blast erosion test rig, sand was ejected from the nozzle by high pressure air to strike the test sample. A sample holder was fixed in the horizontal plane and was designed to maintain the stand-off distance and to varying the test sample angle from 0 to 90°. The double disc process was adapted to estimate the impingement velocity of solid particles.

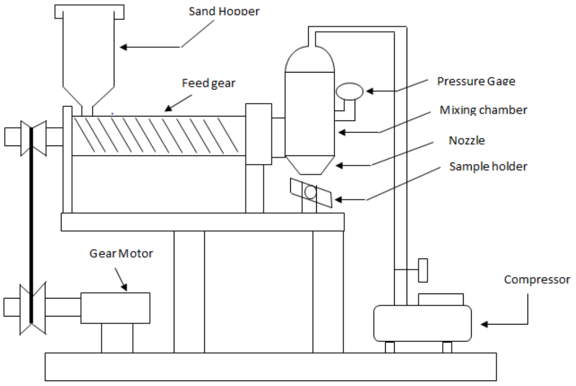


Figure.1:Schematic of the solid particle erosion rig

2.3Signal-to-noise (S/N) ratio

The Taguchi concept emphasizes mathematical modeling to reduce time-consuming of experiments and testing by considering parametric optimization when estimating stable erosion under reasonable factors. Detailed explanation and clarification of controllable experiments to identify the ideal considerations in the DOE (design of experiment) is an effective analysis process. The choice of control and fixed parameters is important in DOE, and, in this respect, a large number of factors are incorporated to identify less important variables as early as possible. In previous studies, erosion of polymers and composites were mainly dependent on the impingement velocity; controlling and constant factors are listed in Table 2. Considering the L27 (4^3) orthogonal array design concept, the significance of four variable factors at four different stages are designated.

Table 2: Setting parameters

Fixed parameters Fixed conditions/values		**Control factor**	**Symbols**	**Level**		
				I	**II**	**II**
Nozzle diameter(mm)	5	Velocity of impact(m/sec)	A	30	40	50
Length of nozzle(mm)	55	Angle of impingement (Degree)	B	30	60	90
Erodent	Silica sand	Erodent size (Micron)	C	300-355	355-500	500-600
Erodent shape	Irregular	Stand-off distance (mm)	D	15	20	25
Erodent feed rate gm/sec	4.56					
Erodent micro-hardness (HV)	42-44					

The number of tests is characterized as a S/N (signal-to-noise) ratio, of which several versions exist based on the type of characteristics. The analyzed ratio related to small amounts of erosive damage is the case of smaller is the better characteristic. Using this approach, this is determined as a logarithmic formulation of the loss function as follows.

In the case of less being the improved quality characteristic, this can be estimated using the following formula:

$\frac{S}{N} = -10log\frac{1}{n}(\sum y^2)$ …… (1)

where n is the number of observations and y is the observed data. Less is regarded as the improved characteristic with respect to the S/N ratio transformation and is suitable for reducing the erosion rate.

3. Results and discussion

3.1Influence of impact velocity

The least-squares fitting of actual data was conducted by applying the power law. Consequently, erodent particle velocities of 30 m/sec, 40m/sec, and 50m/sec at impingement angles of 30°, 60°, and 90°were taken in to consideration for these purposes.

The relationship between stable erosive wear rate (E) and impingement velocity is stated as a simple power function:

E = kv^n …………………. …. (2)

In the above formulation, the velocity exponent *n*, the proportionality constant, *k*, involves the influence of rest of the concerning parameters. The influence of impact velocity on erosion rate of metals and alloys has been investigated to a limited extent. The velocity exponent (*n*) in general varies from 2 to 3 and 3 to 5 which indicate the materials as ductile and brittle nature respectively [10]. The other mechanical properties (hardness, ultimate tensile strength, modulus of elasticity, fracture toughness, yield stress, yield strain and rebound resilience etc.) can be correlated with this designing and characterizing concept.

The fitting parameters are listed in Table 3 and as an example the criteria of fitting calculation is expressed in Fig.2 using GRAPHWIN software. Using the experimental data, the calculated velocity exponents are obtained in the range of 0.8756-1.0867for low carbon steel at different impingement angle. This means that the finding of velocity exponents are almost closer to the exponents range mentioned by the different researchers for conformity of ductile behavior of tested material. In fact, the interesting observation in this study is that, in spite of the standard range for ductile material is within 2 to 3, but it has been found from the experimental data this velocity exponent range is true for only certain lower velocities and lower particle size. But at higher impact velocities, the velocity exponent is higher than that of the standard range. In this context, it can be realized that velocity exponent range varies with impact velocity and particle size. In case of coefficient of determination, relationship quality between erosion rate and impact velocity for exponential parameter is found to be stronger (99%) for test samples.

Table 3: The power law calculated values at different impingement angles

Tested Material	Impingement angle (α, ∘)	*k*	*n*	R^2
Low carbon steel	30	0.002966	0.8873	0.93
	60	0.00305	0.8756	0.97
	90	0.00123	1.0867	0.87

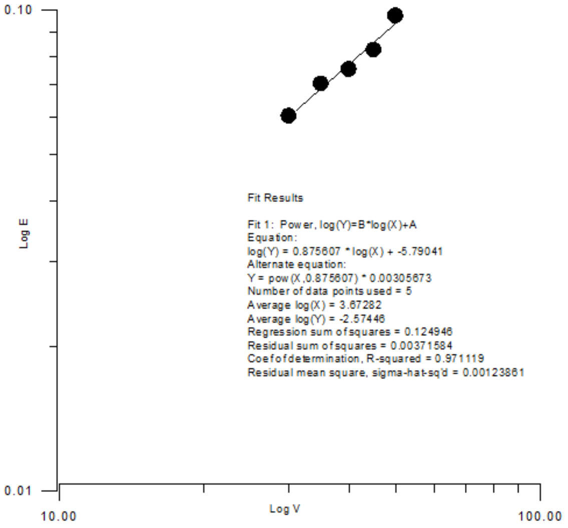


Figure.2: Curve fitting using power law equation for experimental data between erosion rate and impact velocity [impact angle 60 degrees]

3.2 Dimensional analysis

Let:

E_R=F (V, f, P, D) ………………………(3)

Where, E_R-Erosion rate= MT^{-1}, V-Impact velocity= LT^{-1}, f- Sand flow rate= MT^{-1}, P-Particle size=L, D-Distance between nozzle and target material=L.

Let k be a dimensionless constant, then equation (3) can be written as:

E_R= k[V^a. f^b. P^c. D^d] ……………………(4)

Substituting the dimensions of each physical quantity, equation (3) reduces to:

MT^{-1}= k[$(LT^{-1})^a$. $(MT^{-1})^b$. $(L)^c$. $(L)^d$]

or MT^{-1}= k [L^{a+c+d}. T^{-a-b}. M^b] …………..(5)

Since equation (5) must be dimensionally homogeneous, equating the powers of M, L, and T and obtain:

b=1………… …………………………(6)

-a-b=-1 or, a=0 ………………………… (7)

$a+c+d=0$ or, $c=-d$ ……………………..(8)

Therefore

$E_R = k[V^0 . f^1 . P^{-d} . D^d]$

or, $E_R = kf[D/P]^d$

or, $E_R = K[D/P]^d$ …………………………..(9)

Where, “d” and “K” are arbitrary constants.

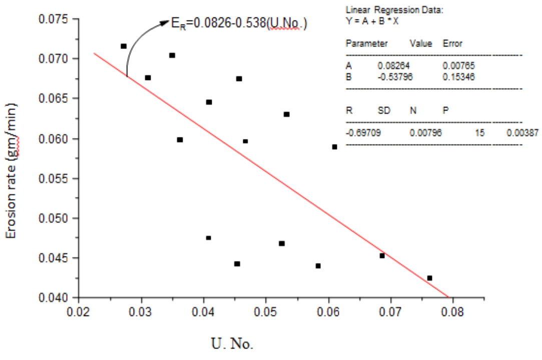
The dimensional parameter D/P mentioned in equation 9 is designated the “ Uttam Number” and can be expressed in brief as U. No.

The relationships between erosion wear (E_R) and U. No. for low carbon steel under an impact velocity of 50 m/sec and impact angle 30^0 are displayed in Figure 8.

The curves show that erosion rate decreases linearly with increased U. No. and is represented by the following equation:

$E_R = 0.0826-[0.538(U. No.)]$ For low carbon steel

In Figure 3, rectangular data points indicate the test observations of erosion rate with U. No. Using these actual data, least squares equations and correlations were produced using ORIGIN software. The solid lines in the figure indicate trend lines. The correlation coefficient (r) was calculated to obtain-0.69709 for the test material. Therefore, the actual data figure ensures acceptable recognition with the theoretical model.



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Linear Regression Data:
Y = A + B * X

Parameter    Value      Error
---------------------------------
A            0.08264    0.00765
B            -0.53796   0.15346
---------------------------------

R          SD         N     P
---------------------------------
-0.69709   0.00796    15    0.00387
---------------------------------
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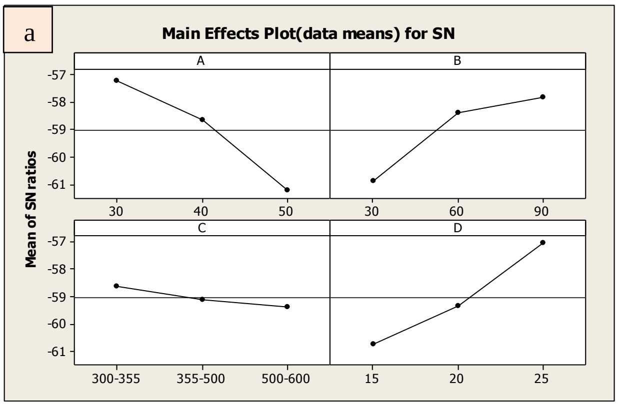
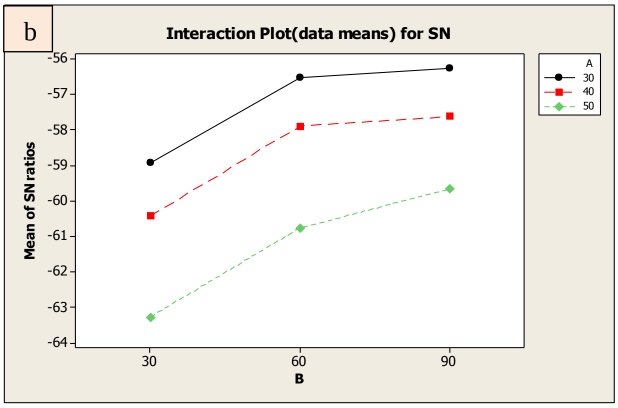
Figure.3: Erosion rate as function of U. No. for low carbon steel

3.3 Steady state erosion of low carbon steel

S/N ratio in the context of erosive wear rate indicates the arithmetic mean of two replicates. Considering all the S/N ratios of the erosive wear rates, the average S/N ratio was – 59.041 dB. The graphical presentation of the main effect plot of S/N ratio is shown in Figure 3(a), emphasizing the consequence of the four variable parameters on erosive wear rate. An uncomplicated model is required to predict performance with respect to the probable interrelationships between the parameters; we used MINITAB 15 for this purpose. Factorial reflection integrated in a easier manner demonstrates the interaction effects, and an analysis of test outcomes was bused to interpret among factor combinations of A1, B3, C1, and D3, which contributes to the evaluation of the lowest erosive wear rate. The relationship between selected control factors are shown in Figure 3 (b, c, d), which indicates that to obtain a minimum level of erosion, factors A, B, C, and D are all involved. Comparing the interactions in Figure 4(b, c, d), the interaction of A× C is the most important determinant of erosive wear rate. Even though factors A and B have a larger impact on output performance, in the case of combined interrelationships they have a smaller effect on erosive wear rate. In a similar way, while factors B and C separately have a greater effect on output performance, their interaction has a reduced effect on erosive wear rate.





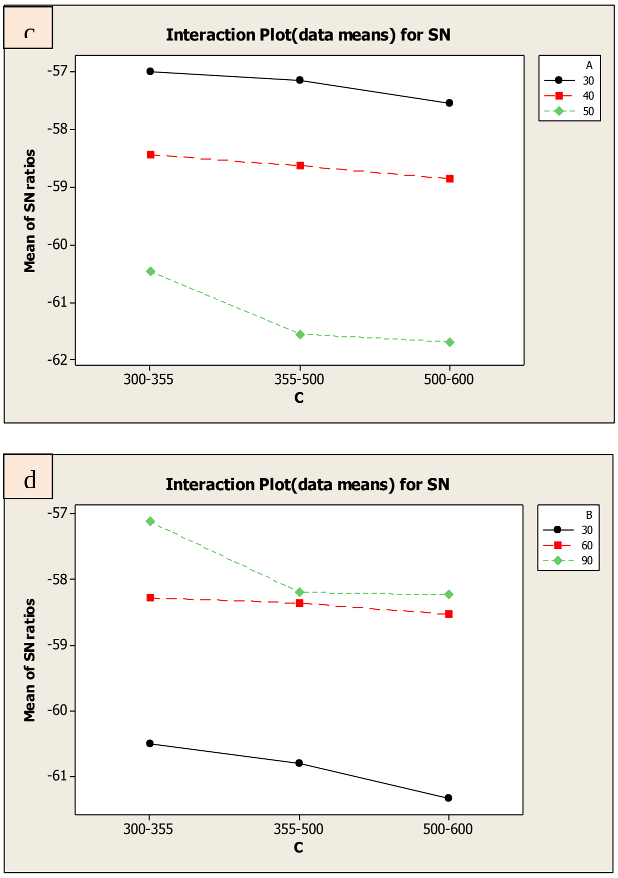


Figure.4: Main effect plot (a), Interaction graph between (b) A × B, (c) A× C, and (d) B× C for erosion rate of low carbon steel

3.4 ANOVA and the effects of low carbon steel

Analysis of variance (ANOVA) is a decision-making methodology for confirmation of the significance of the level of effect of the factors considered. In addition, ANOVA is tool for selecting more meaningful factors. The results of ANOVA for the analysis of the contribution of factors on erosive wear rate are shown in Table 4; a significance level of 5% was considered. The p-values show that the main effects on erosion rate, namely impingement velocity, impingement angle, stand-off distance, and erodent size have a high level of significance. In the case of a comparative analysis of interaction between different factors, B*C = interaction with in impingement velocity ∗ erodent size (p = 0.469) has a lower p-value than the other two combinations. However, the factor interaction A*B= velocity of impact * angle of impingement (p = 0.500), contributes less to erosive wear rate compared to A*C=angle of impingement*erodent size (p=0.508).

Table 4:ANOVA table for erosion rate of low carbon steel

Source	DF	Seq SS	Adj SS	Adj MS	F	p	% p
A	2	73.9488	73.9488	36.9744	139.45	0.000	37.16
B	2	46.8414	46.8414	23.4207	88.33	0.000	24.65
C	2	2.5079	2.5079	1.2539	4.73	0.058	1.32
D	2	62.0397	62.0397	31.0198	116.99	0.000	32.65
A*B	4	0.9987	0.9987	0.2497	0.94	0.500	0.52
A*C	4	0.9809	0.9809	0.2452	0.92	0.508	0.51
B*C	4	1.0758	1.0758	0.2690	1.01	0.469	0.56
Error	6	1.5909	1.5909	0.2652			0.83
Total	26	189	9841				

3.5 Confirmation experiment for low carbon steel

The End level of Taguchi approach is the validation of experimental observations for analyzing the quality characteristics. The validity of test results is ensured by concerning an arbitrary set of factor level combination and after that it has been compared with the test results. The measured S/N ratio for wear rates are estimated in connection with the predictive equations:

$$\bar{\eta} = \bar{T} + (\bar{A}_2 - \bar{T}) + (\bar{B}_3 - \bar{T}) + (\bar{C}_2 - \bar{T}) + (\bar{D}_1 - \bar{T})\ldots \quad (10)$$

Where $\bar{\eta}$ is the predicted average;$\bar{T}$ is overall experimental average;
$\bar{A}_1, \bar{B}_2, \bar{C}_1$ and $\bar{D}_2$ is the mean response for factors at designated levels.

By combining like-terms, the equation reduces to

$$\bar{\eta} = \bar{A}_2 + \bar{B}_3 + \bar{C}_2 + \bar{D}_1 - 3\,\bar{T} \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

A new combination of factor levels A2, B3, C1 and D2 is used to predict deposition rate through prediction equation and it is found to be. $\bar{\eta}$ = - 59.210 For each performance measure, an experiment was conducted for a different factors combination. The Predicted (A2, B2, C1, D2) and experimental (A2, B2, C1, D2) S/N ratio are calculated as -59.21 and -59.080dB respectively. The new generated model is very meaningful for the predicted erosive wear rate within a justifiable accuracy. The error level or deviation of S/N ration is very small between the predicted and experimental data which is nearly about 0.726 %. After all, the accuracy level can be improved more precisely in case of increase of the number of measurements. This validation approach incorporates the generation of the mathematical model for the prediction of measures of performance on the basis of knowledge of the input parameters.

4. Conclusions

The erosion results of low carbon steel have been provided some new findings in relevant to different operating parameters. The validation of results and correlation of erosion with friction, Uttam number, artificial neural network, ANOVA, erosion efficiency, S/N ratio methodology concept has made the realization of novelty of the erosion study of this low carbon steel. The correlation of erosion rate with U. No. and relationship between erosion rate and friction factor provides the fairly good agreement. This correlation can be used as a significant tool for future study. The erodent size and stand-off distance provides new insight of relation of these parameters with erosion rate under clarification of possible trends. The average S/N ratio –59.041dB and Taguchi design concept ensures the validation of experimental and theoretical results. The predicted and experimental S/N ratio fluctuations within range 0.726% and ANOVA method ensures the identity of main dominating factors distinctly or as an interaction on erosion of the tested low carbon steel. It is expected that the analysis of this new or novel concern relating to low carbon steel can be used as an authentic sources in industry and future researches for the applications of this material in different concerned mechanical and tribological systems.

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6. NOMENCLATURE

Symbol	Meaning	Unit
ANOVA	Analysis of variance	Dimentio-nless
ER or E	Erosion rate	(gm/sec)
MS	Mean square	Dimentio-nless
V	Impact vlocity	m/sec
n	Velocity exponent	Dimentio-nless
SS	Sum of squares	Dimentio-nless
S/N	Signal to noise ratio	Dimentio-nless
U.No	Uttam number	Dimentio-nless
DF	Degrees of freedom	Dimentio-nless
K	Proportionality con0stant	Dimentio-nless