A Selection of Operating Condition of AISI 4140 Steel for Tribological Properties

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ABSTRACT

In this study, the Nitride and WCC coated AISI 4140 alloy steel to experimentally tested and analyzed to improve tribological. Selected AISI 4140 steel is optimized for tribological test settings using the grey relational analysis method. Taguchi method is implemented for experimental design which gives nine experimental runs based on orthogonal array. Coefficient of friction (COF) and wear is measured for nine different test on Pin on disc Tribometer. The optimal setting for Nitride and WCC coated AISI 4140 alloy steel and confirmation test is performed which gives clear indication of optimum operating condition for AISI 4140 steel.

Keyword –Nitriding, Coating, Gray Relation Analysis, Signal to Noise Ratio

INTRODUCTION

In the recent century tremendous amount of development is carried out in the field of Tribology and surface engineering. Most of the research is focused to improve the wear resistance of industrial materials and applications. Metal deposition and coating techniques are used for improving the friction loss in the industrial application, thereby increasing the life span of materials. Hence, to improve wear resistance, surface roughness, and texture research, extensive research is carried out which includes the addition of a coating or metal deposition on the surface of materials[1,2]

High hardness, great grip to the substrate, high Chemical dependability, and low- coefficient of friction make these multi-layered structures great alternatives to decrease wear[3]. Particularly, hard covering testimony is one of the essential components of influence as rapid cutting innovation creates[4]. Thin hard coatings saved by physical vapour testimony (PVD), e.g. WC/C are often used to enhance tribological execution in many designing applications. As a rule single covering can't take care of the wear issues. The blend of nitriding and hard covering permits the creation of duplex coatings, which are recognized by a high obstruction against complex burdens, since the benefits of both individual procedures are joined here[5]. Nonexclusive materials property information, for example, hardness, benefit temperature, and coefficient of erosion exist for some coatings, however encounter has demonstrated that the substrate and covering carry on as a framework and must be assessed together notwithstanding guaranteeing that the testing conditions are important to the use of intrigue[6]. Utilization of coatings on instruments and machine components is extremely efficient method for enhancing their erosion and wear opposition properties in wide scope of uses[7,8] .

The material is tested to determine the optimum operating condition in order to have a low COF and wear rate. The operating conditions vary based on design of experiment using Taguchi method[9]. L9 orthogonal array is implemented for the measurement of COF and wear rate on pin-on-disc Tribometer. The Grey relation method[10,11,12] is utilized to convert multi-output response into the single output response. Then SN ratio analysis, ANOVA[13], and confirmation test is carried to ensure the fitness of the model and to identify optimum operating conditions.

METHODS AND TESTING

The Nitride and WCC coat AISI 4140 alloy steel were tested under the tribological test condition.

Design of Experiment (DOE)

The experiments are performed to investigate the tribological behaviour of coatings for different test conditions for Nitride and WCC coated AISI 4140 steel. The DOE is utilized for experiments for proper experimentation. In this research DOE by Taguchi Method used to reduce number of experiments. The tests are performed for three different test parameters, namely load, speed and sliding distance. The range contact pressure acting on the coatings are varied from 0.5 kg to 1.5 kg, speed is varied from 750 RPM to 1250 RPM and sliding distance is varied from 0.5 km to 1.5 km. The design of experimentation of three parameters and 3 levels as shown in Table 1.

The full factorial design of above problem requires 3^3=27 run so as to reduce the number of runs, Taguchi design of L9 orthogonal array is used .The Design Points are illustrated in Table 2.

Table: 1 DOE design variable (factor) and Level

	Level		
Factor	1	2	3
Load (Kg) (A)	0.5	1	1.5
Speed (RPM) (B)	750	1000	1250
Sliding Distance (Km) (C)	0.5	1	1.5

Table: 2 L9 Orthogonal arrays designed by Taguchi method

Trial No	Load (kg)	Speed (RPM)	Sliding Distance (m)
1	0.5	750	500
2	0.5	1000	750
3	0.5	1250	1000
4	1	750	750
5	1	1000	1000
6	1	1250	500
7	1.5	750	1000
8	1.5	1000	500
9	1.5	1250	750

The Tribological testing of selected materials is carried out on pin on disc Tribometer as shown in Figure1. A Specimen is created Based on ASTM G99 04 standard. The cylindrical and spherical shape specimen is required for the Pin on disc Tribometer. The cylindrical specimens of diameter of 10 mm and 20 mm height are prepared. The Disk is made up of EN 8 material having diameter 160 mm and thickness of 8 mm which was electroplated. The pin on disc specimens are shown in Figure2.

Figure1 Pin on Disc Tribometer

(a) (b) (c) (d) (e)

Figure2 Wear and COF Test specimen of AISI 4140, (b) Nitrided AISI 4140, (c) Nitrided and TiN Coated AISI 4140, (d) Nitrided and TiAlN Coated AISI 4140, (e)Nitrided and WCC Coated AISI 4140

The pin specimen is rubbed on EN 8 Disc and the track radius is changed according to the parameter decided. The wear and coefficient of friction measured by using the displacement of pin by Linear Variable Differential Transducer. The Figure3 shows the specimens after the testing.

(a) (b) (c) (d) (e)

Figure3 After Wear and COF Test specimen of AISI 4140, (b) Nitrided AISI 4140, (c) Nitrided and TiN Coated AISI 4140, (d) Nitrided and TiAlN Coated AISI 4140, (e)Nitrided and WCC Coated AISI 4140

Grey relation analysis (GRA)

Most of the researcher preferred GRA Taguchi Analysis to find the optimal response for multi-output response, for this particular study wear and coefficient of friction are the two output responses. Taguchi method could be used effectively for establishing optimal parameter setting for the single performance characteristics.

Grey-Taguchi method is considered due to the presence of multiple performance characteristics with conflicting goals.

Each output response is having their specific criteria based on that GRA normalized the values as follows

(i) Benefit Criteria

$$Y_{ij} = \frac{x_{ij} - \underset{j}{\text{Min}}\, x_{ij}}{\underset{j}{\text{Max}}\, x_{ij} - \underset{j}{\text{Min}}\, x_{ij}} \quad (1)$$

(ii) Cost Criteria

$$Y_{ij} = \frac{\underset{j}{\text{Max}}\, x_{ij} - x_{ij}}{\underset{j}{\text{Max}}\, x_{ij} - \underset{j}{\text{Min}}\, x_{ij}} \quad (2)$$

Where x is the actual value of ith Experiment (alternative) and j^{th} response (Criteria).

The ideal sequence for each response is Y_{oij}. Grey relational coefficient (ξ) can be calculated using Eq. (25) .

$$\xi_{ij} = \frac{\Delta_{min,j} - \varphi\Delta_{max,j}}{\Delta_{oij} - \varphi\Delta_{max,j}} \quad (3)$$

Where

$$\Delta_{oij} = |Y_{oj} - Y_{ij}| \quad (4)$$

Δ_{0ij} Is the absolute difference. After calculating the absolute differences of all responses, $\Delta_{min,\ j}$, $\Delta_{max,\ j}$ of each response is calculated. ψ Value ranges from 0 to 1, to have better results. Generally a value of ψ to be considered is 0.5.

To determine grey relation grade of each experiment weightage of respective criteria's or response variable is required. The Grey Relation is calculated by Eq. (5).

The Grey relation grade is calculated with the help of weights of each response by using Eq. (27),

$$\gamma_i = \sum_{j=1}^{n} \xi_{ij}\, \beta_j \quad , \sum \beta = 1 \quad (6)$$

Where β is the weightage of jth response (criteria)

In a Grey relation analysis higher grade gives the best or optimal performance for a given parameter.

Wear and coefficient of friction (COF) were measured, hence GRA method is used to find optimal settings. The weightage of the Wear and Coefficient of friction is determined to help by Entropy method

Entropy method

The AHP method determines weightage of each criteria's based on relative importance one criteria over another which depends upon literature, application, and the experience of researcher, so there might be variation in assigning the value of a_{ij}. However Entropy method is an objective weighting method which uses probability theory which measures the uncertainty in output responses of each criteria to determine weightage of each criteria.

To determine the weights by using Entropy method, first output responses of each criteria is normalized and stored in decision matrix by using Eq. (7).

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad ; i = 1, 2, , \ldots, m;\ j = 1, 2, \ldots\ldots, n \quad (7)$$

Where x_{ij} are the values respective to i^{th} alternative and j^{th} criteria.

Also m is number alternatives the selected for the system and n is the number of criteria selected for analysis.

The Entropy value T_j of jth criteria is calculated with the help of following Eq. (8). The K value is calculated based on the number of alternative presents. K is a constant which normalizes Entropy Values between 0 and 1

$$k = 1/\ln m$$

$$T_j = -k \sum_{i=1}^{m} N_{ij} \ln N_{ij}, \quad ; i = 1, 2, , \dots, m; \; j = 1, 2, \dots\dots, n \,. \tag{8}$$

The degree of divergence (d_j) of jth criteria is calculated by using Eq. (9)

$$d_j = |1 - T_j| \tag{9}$$

The Normalization of degree of divergence for all criteria gives us the weight values as given in Eq. (10)

$$En_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{10}$$

. The output responses like Wear and COF are normalized with Eq. (7). The Final weightage for Wear and COF is determined by Eq. (10).

RESULTS AND DISCUSSION

The grey relation analysis is performed on COF and wear responses of 9 experiments. First, The Normalization of output responses of COF and Wear are calculated with help of Eq.1 and Eq. 2 for respective criteria. In Table 3, column 1 and 2 represents the output responses Wear and COF measured on Pin on Disc Tribometer. The normalized value of each response is shown in column 3 and 4, and differences in each sequence are shown in column 5 and 6 of Table 3.

Grey relation coefficients (ξ) are calculated for each response using Eq. (3). By considering weights for wear 0.4981 and COF 0.5019. , the overall grey relation grades were calculated by using Eq. (5) this value is shown column 9 of Table 3.

Table: 3 Output responses and Grey relation coefficients and grade

	Output Response		Normalized Value				Grey relational coefficient		Grade
Trial No	WEAR (1)(µm)	COF (2)	X2 (3)	X2 (4)	Δ_{01} (5)	Δ_{02} (6)	ξ_1 (7)	ξ_2 (8)	γ (9)
1	8.32	0.59	0.9328	0.5385	0.0672	0.4615	0.8815	0.5200	0.6987
2	8.75	0.73	0.8478	0.0000	0.1522	1.0000	0.7667	0.3333	0.5475
3	7.98	0.715	1.0000	0.0577	0.0000	0.9423	1.0000	0.3467	0.6696
4	9.35	0.65	0.7292	0.3077	0.2708	0.6923	0.6487	0.4194	0.5327
5	12.68	0.71	0.0711	0.0769	0.9289	0.9231	0.3499	0.3514	0.3506
6	13.04	0.58	0.0000	0.5769	1.0000	0.4231	0.3333	0.5417	0.4387
7	8.64	0.47	0.8696	1.0000	0.1304	0.0000	0.7931	1.0000	0.8977
8	9.52	0.62	0.6957	0.4231	0.3043	0.5769	0.6216	0.4643	0.5420
9	8.21	0.59	0.9545	0.5385	0.0455	0.4615	0.9167	0.5200	0.7160

Thus GRA method converted the multi-output response into a single output response which will help us to analyze the single response by using Signal to Noise ratio (S/N ratio). S/N ratio is used to measure the variation of each output response variable with others. As GRA gives the grade value in the form of higher is better, S/N ratios of higher is better criteria is given as follows

$$SN_i = -10 \times \log_e \left[\frac{1}{N_i} \sum_{k=1}^{N} \frac{1}{y_k^2} \right] \qquad (11)$$

Where i = experiment number, k = repetition number, Ni=Number of repetitions for an experiment i and y *is the output response*.

The signal-noise ratio of each factor, mean signal noise ratio and ranking of each factor (according to the effect) is explained in Table 4. The graphical representation of Signal to Noise ratio for three factors, namely, Load (A), Sliding Speed (B) and Sliding Distance (C) are shown in Figure4.

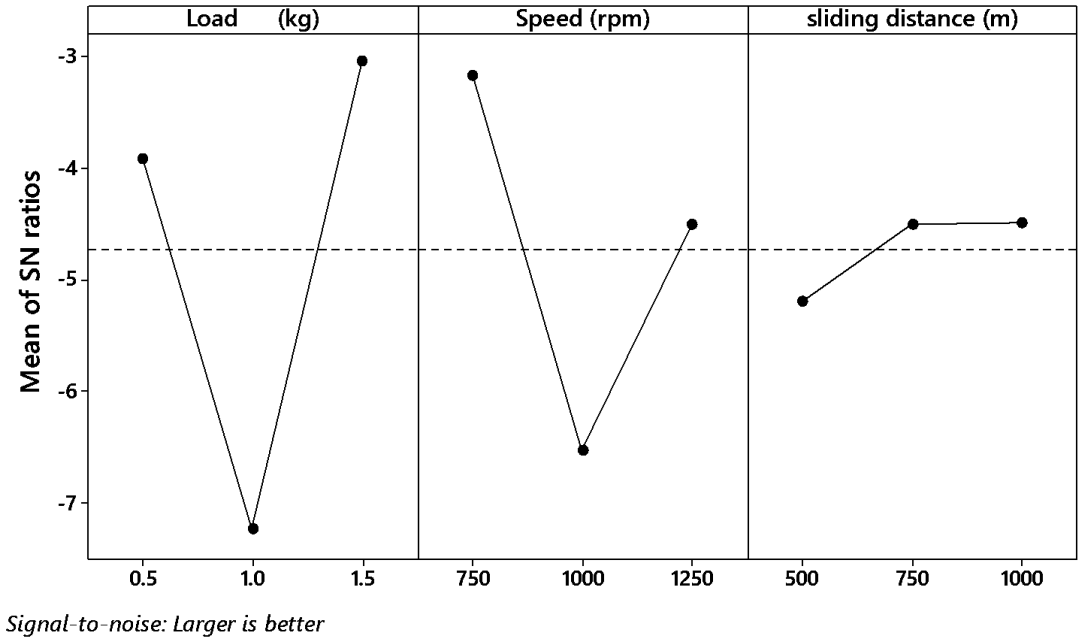

Figure4 Plot of Maximum S/N Ratio with respect to levels

Table: 4 S/N ratio corresponds to levels and Factor with a ranking of the importance of the factors

Level	Load (kg)	Speed (RPM)	Sliding distance (m)
1	-3.918	-3.166	-5.193
2	-7.244	-6.539	-4.514
3	-3.046	-4.502	-4.5
Delta	4.198	3.373	0.693
Rank	1	2	3

ANOVA Analysis

Analysis of variance is carried out to determine the significance of input parameters on the output parameters based on the P - test. The correctness of the model developed is checked by using R^2 and R^2 adjusted values. The percentage contribution of each parameter is calculated with the help of adjusted sum of squares.

The ANOVA is carried out on the L9 orthogonal array for grey relation grade with help of MINITAB mathematical software results are illustrated in Table 5. Load and Speed are having P values less than 0.05 which indicates that both parameters are significant in the model. The R^2 and R^2 adjusted value for the model found to be 98.34 % and 93.38%.As the difference between the two values are less than the 20% means the model is Valid.

Table: 5 ANOVA Test Model

Source	Degree of Freedom	Adjusted Sum of Squares	Adjusted Mean of Squares	F-Value	P-Value	Contribution In Percentage	Significance
Load	2	0.1235	0.0617	34.56	0.028	57.21%	Significant
Speed	2	0.0792	0.0396	22.18	0.043	36.72%	Significant
Sliding Distance	2	0.0095	0.0047	2.66	0.273	4.41%	Not Significant
Error	2	0.0035	0.0017				
Total	8	0.2159					
Model	Summary						
Standard Deviation	R-square	R-square (adjusted)					
0.04228	98.34%	93.38%					

Confirmation test

As the optimal setting parameters are selected based on SN ratio plot for improvement in performance. The Confirmation test carried out to predict and check optimal parameter settings are in reality gives the improved performance than initial parameter settings. The estimated S/N ratio $\hat{\gamma}$ Is the predicted value of the SN ratio for optimal parameter as described in Eq. (12).

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{n} (\widehat{\gamma_m} - \gamma_i) \qquad (12)$$

Where, $\widehat{\gamma_m}$ is total mean of SN Ratio, γ_i is mean of the S / N ratio for optimum parameter setting to respective level of each parameter, and n is number of main design factors that affect the output responses.

The initial testing is carried out on parameter settings as load 1 kg, 1000 RPM, and 1000 m (A2B2C2). The COF and Wear are measured on the Pin on Disc Tribometer, wear is found to be 12.68 microns and COF is 0.71. The SN ratio (-9.08294) is calculated for the initial setting by Eq.11 and Grey relation grade is calculated to be 0.3514.

After obtaining the optimal parameter setting for the plot of the Mean SN ratio. The Optimum process parameter selected as load 1.5 kg, Sliding speed 750 RPM and sliding distance 1.5 km (A3B1C3), The Experimental test is carried out on optimal parameter setting to find wear and COF. The predicted values for optimal setting are calculated with help of Eq. (12).The Prediction value for optimal setting are SN ratio=-1.2394 and GRG=0.8670 which is comparable to the experimented values of SN ratio=-1.2695 and GRG=0.8640. As the optimal GRG is improved by 0.51 from initial parameter setting which suggest much more improvement in performance. The Table 5 shows the confirmatory test results.

Table: 5 Confirmation test.

	Initial Combination	Optimal Combination	
		Prediction	Experimentation
OPERTAING SETTING	A2B2C2	A3B1C3	
S/N RATIO	-9.08294	-1.2394	-1.2695
WEAR(µ)	12.68		7.93
COF	0.71		0.49
GREY RELATION GRADE	0.3514	0.8670	0.8640

CONCLUSION

This study proposes better way to select material for tribological applications with help of different mechanical properties by using MCDM methods.

Nitride deposited and WCC coated material is tested to optimize operating condition for the AISI 4140 steel on "PIN ON DISC" Apparatus by Using Taguchi Method. Wear and coefficient of friction were the criteria's used for multi-criteria optimization with the help of grey relation method, The results show the optimal operating settings for Nitride deposited and WCC coated AISI 4140 steel is A3B1C3 (load 1.5 kg, Sliding speed 750 RPM and sliding distance 1 km).

Moreover the Optimized operating settings show improvement of COF and Wear rate up to 0.41 for grey relation grade value than the initial operating settings.

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