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RESEARCH

Tribological Performance Optimization of Electroless Ni-P-W Coating Using Weighted Principal Component Analysis

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A B S T R A C T

The present investigation is an experimental approach to deposit electroless Ni-P-W coating on mild steel substrate and find out the optimum combination of various tribological performances on the basis of minimum friction and wear, using weighted principal component analysis (WPCA). In this study three main tribological parameters are chosen viz. load (A), speed (B) and time(C). The responses are coefficient of friction and wear depth. Here Weighted Principal Component Analysis (WPCA) method is adopted to convert the multi-responses into single performance index called multiple performance index (MPI) and Taguchi L_{27} orthogonal array is used to design the experiment and to find the optimum combination of tribological parameters for minimum coefficient of friction and wear depth. ANOVA is performed to find the significance of the each tribological process parameters and their interactions. The EDX analysis, SEM and XRD are performed to study the composition and structural aspects.

1. INTRODUCTION

Most of the engineering components undergo relative motion due to which the wear takes place in the surface of the components and become useless after a certain period of time. But the lifetime and performance of these engineering components can be improved by applying hard coatings over the surface of the components. So surface coating is one of the solutions to the engineering materials for having a long working life. Among the coating procedures, over 95 % of metal deposited from aqueous solution is electroplated. There are three reasons for this. Firstly, electroplating is technically more straight-forward than electroless deposition. Secondly, a far greater range of metals and alloys can be electrolytically deposited than is the case with electroless method. Thirdly, electroplating is less expensive than electroless deposition. For these reasons, electroless deposition is of industrial importance manly for copper, nickel and some nickel based alloys. In spite of these somewhat negative notes, it can be said that the industrial use of electroless deposition methods continues to increase for its good anti-corrosion, anti-friction and wear protection properties. Electroless has several advantages over electroplating technique, except the life of the bath. The advantages include the quality of the deposit, namely the physical and mechanical properties. In this process, a sharp edge receives the same thickness of deposit as a blind hole does i.e., the uniformity of the coating and it offers extremely bright deposits, which are comparable with electroplated bright nickel. The desirable properties can be varied by choosing different pH, temperature and composition of the bath. Electroless nickel coatings has assumed the greatest commercial importance among the electroless coating.

Since the discovery of electroless/chemical coating process in 1946 by Brenner and Riddell [1], a series of research studies have been performed and the process is accepted by various industries like electrical, aerospace, automotive, chemical, electronics, etc [2,3]. In electroless plating technique many metals like nickel, copper, gold, silver, palladium and cobalt are being deposited. The industrial uses of electroless nickel especially the nickel/phosphorus alloy has grown steadily during the last decade, because of its unique properties. The autocatalytic deposition of almost pure nickel using hydrazine as the reducing agent has been known for many years, but this process has found little industrial usage. The nickel/phosphorus or boron alloys are mostly regarded as synonymous for the word 'electroless' because 95 % of industrial productions are of these alloys [4-7]. Hypophosphite reduced nickel-phosphorous and borohydride reduced nickel-boron coating have already gained immense popularity particularly due to excellent hardness, anti-corrosion and tribological properties [8-10]. Remarkable improvement in the wear resistance of the coatings has been reported when hard particles are incorporated [11]. Choice of the particles depends on the desired property. In the field of tribology, nickel based composite coatings can be divided into two major categories, i.e., lubricating composite coatings and wear-resistant composite coatings. The wear-resistant composite coatings usually have co-deposited hard particles such as W, SiC, Al_2O_3, B_4C and diamond, and they usually have increased hardness and wear resistance as compared with binary Ni-P coating. Pearlstein and Weightman [12] first presented the Ni-P-W ternary alloy in 1963 and since then, many investigations on Ni-P-W ternary alloy are reported. Wear, roughness and friction measurement carried out on electroless nickel coatings [13-21] reveals that with the increase of tungsten content the wear resistance of the coating increases under various loading condition. This is due to the solid solution strengthening by tungsten of nickel matrix. The coefficient of friction is found to be high and further increased with the increase of applied normal load. The frictional coefficient is found to be higher in as-plated condition compared to heat-treated condition. All these studies aim to have the better tribological properties or hardness of the coating or the characteristics of the deposition on the basis of the composition of chemicals of the coating and the heat treatment temperature. But the wear rate or coefficient of friction of the hardest Ni-P-W coating (based on chemical composition and heat treatment temperature) may vary due to different composition of the tribological parameters like load, speed, time, type of lubricants etc.

As the Ni-P-W ternary alloy coating has emerged as a hard coating in the field of tribology so the tribogical parameters like load, speed, time, lubricant etc. are needed to be optimized for the better tribological behavior of this coating. Hence, the present investigation is formulated into an optimization problem based on WPCA together with Taguchi method, so that the optimum combination of tribological parameters (load, speed and time) for minimum friction and wear depth can be predicted and also the influence of those parameters on the tribological behaviour of Ni-P-W coating can be better understood. Moreover the coating is characterized with the help of scanning electron microscopy (SEM), energy dispersive x-ray analysis (EDX) and x-ray diffraction analysis (XRD) in order to understand the microstructural characteristics of coatings.

2. EXPERIMENTAL DETAILS

2.1 Coating Deposition

Square shaped Mild steel specimen of size 20 mm × 20 mm × 8 mm is used for the deposition of Ni-P-W coating. This particular dimension of the substrate is chosen in accordance with its substrate holder in the multi tribotester apparatus where the sample has to be fitted for tribological testing. Shaping parting and milling operation is performed sequentially to prepare the specimens from the raw material. Finally surface grinding process is employed to make the surface of the blocks smooth enough because the tribological characteristics of a surface may depend on its surface roughness. Now, as electroless nickel coatings generally follow the surface profile of the substrate, the prepared substrates in the present study should have similar surface roughness. Hence, all the substrates before coating are subjected to roughness evaluations (center line average values, R_a) and the substrates which showed as little as about 0.1 % variation in roughness are selected for electroless Ni-P-W coatings. The roughness measurements are carried out using a surface profilometer (Taylor Hobson, Surtronic 3+). The samples are cleaned from foreign matter and corrosion products by wiping. After that, surfaces of the mild steel specimens are cleaned using distilled water. The specimens, after thorough cleaning, are etched with 50% hydrochloric acid for 1 min. Subsequently, they are rinsed in distilled water followed by methanol cleaning prior to coating. The electroless bath consists of 20 g/l Nickel sulphate, 20 g/l Sodium Hypophosphite, 35 g/l Sodium Citrate, 30 g/l Ammonium Sulphate, 5 g/l lactic acid and 15 g/l Sodium Tungstate. The temperature of the bath was maintained at 90 ˚C and the pH was maintained at 8 by monitoring with a digital pH meter. Before placing the substrate in to the bath each sample is activated by dipping in to palladium chloride solution kept at 55 ˚C. Activated samples are then submerged into the chemical bath and kept for 3 hours for deposition. The coating setup is shown in Fig 1. After the deposition, the samples are taken out of the electroless nickel bath and washed in distilled water. Then the samples are heat treated in a box furnace at 400 ˚C for 1 hour.

2.2 Friction and wear measurement

The experiment was carried out with three controllable three level factors of tribological measurement process i.e., wear depth and coefficient of friction. The three controllable tribological factors are applied load (A), rotational speed (B) and time (C). The values of the tribological test parameters for the friction and wear tests are shown in Table 1. As in this experiment three varying factors with three equally spaced levels (values) are considered, so the total number of combinations of these three factors is $(3)^3 = 27$, with which the experiments can be carried out.

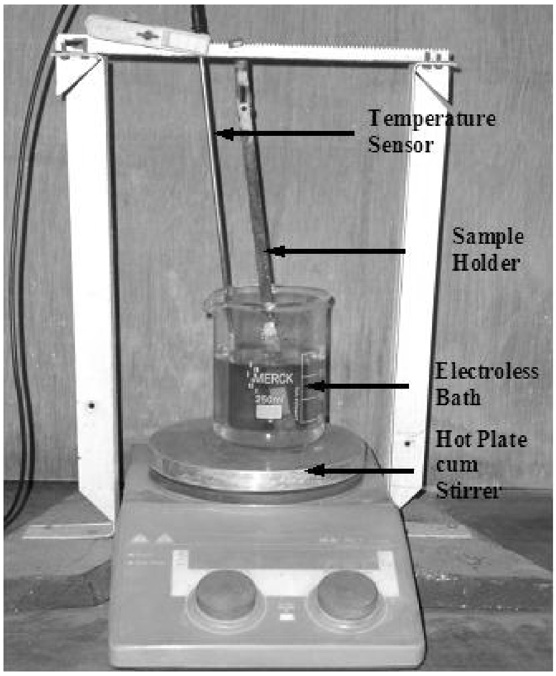


Fig. 1. Electroless coating setup.

Table 1. Design factors and their levels.

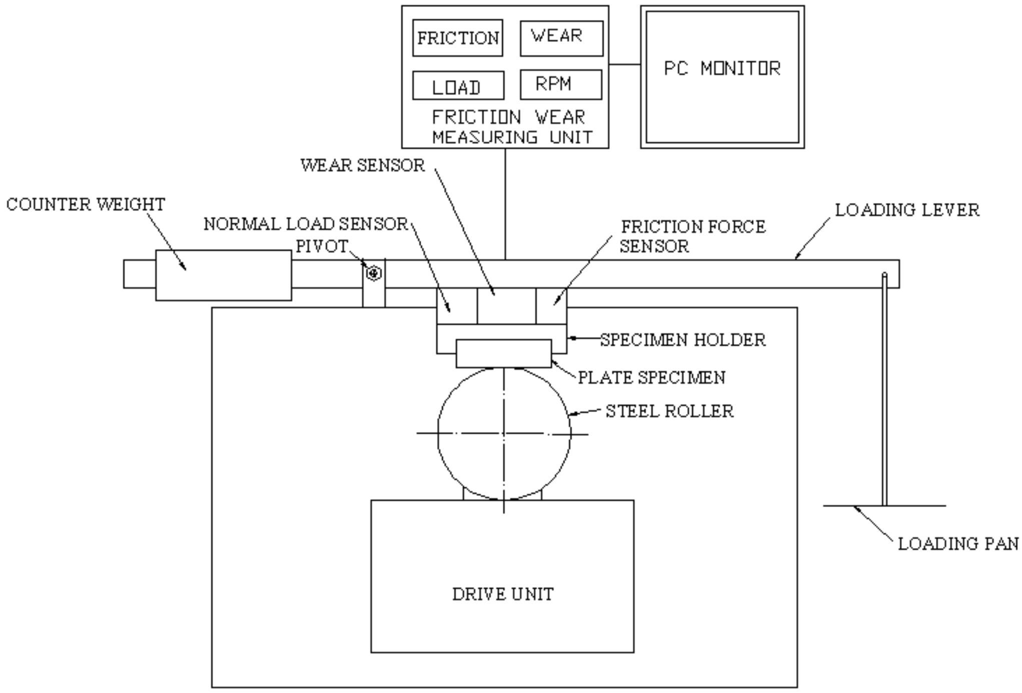
Design Factors	Unit	Levels		
		1	2	3
Load (A)	N	50	75[a]	100
Speed (B)	R.P.M	60	70[a]	80
Time (C)	Min.	5	10[a]	15
a: initial condition				

But the full factorial design of experiment is replaced by a less expensive, faster, partial factorial experiment, i.e., Taguchi's design of experiment for carrying out the experiments in systematic manner. Taguchi's design for the partial factorial is based on specially developed orthogonal array (OA). As it is a three factor three level experiment, so the total degrees of freedom considering the individual factors and their interactions are 18. Here L_{27} orthogonal array is chosen as it has 26 degrees of freedom which is higher than 18. Taguchi's OA consists of 13 columns and 27 rows, which is shown in Table 2.

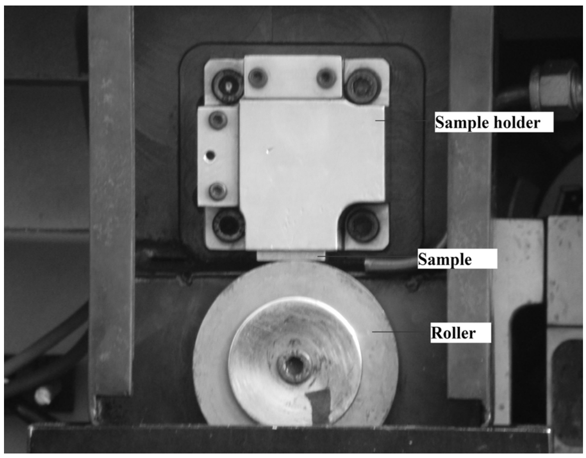
Table 2. L_{27} Orthogonal Array with design factors and interactions.

Trial No.	Column Numbers												
	1 (A)	2 (B)	3 (A×B)	4 (A×B)	5 (C)	6 (A×C)	7 (A×C)	8 (B×C)	9 -	10 -	11 (B×C)	12 -	13 -
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Each row indicates the possible combination of experimental run, with which total 27 experiments are carried out and each column indicates a specific factor or interaction of factors. In this OA the first column is assigned to the factor load (A), the second column is assigned to speed (B) and the fifth column is assigned to time (C). The 3rd, 4th, 6th, 7th, 8th and 11th column are assigned to two way interactions and the remaining columns are for error terms. The cell values in the main factor columns (i.e., A, B and C) indicate the level of corresponding factor. For interaction columns it represents the combination of the main factors, i.e., in the 1st row the cell value of 3rd column is 1 and the cell value of 4th column is 1, it means in this experimental run the interaction between A × B consists of level 1 of factor A and level 1 of factor B. In this manner there are 9 such combinations will be obtained (11, 12, 13, 21, 22, 23, 31, 32 and 33) in the 3rd and 4th column. The remaining interaction columns are same. With these 27 combinations of experimental factors the wear depth and friction coefficient of each heat-treated Ni-P-W coated specimens are measured using a multi-tribotester with block on roller configuration (DUCOM, TR-25) under non-lubricated condition at 28 °C with 85 % RH. The Ni-P-W coated specimens serve as test specimens which are held horizontally against a rotating roller of 50 mm diameter × 20 mm thickness. The experimental setup is shown in Fig 2. The steel roller is coated with titanium nitride of hardness 85 HRC, which is higher than the hardness of the Ni-P-W coated specimen in order to ensure that the wear will take place only in the test specimens.



(a)



(b)

Fig. 2. (a) Block diagram of tribological test setup, (b) Actual block on roller setup.

Dead weights are placed on the loading platform which is attached at one end of a 1:5 ratio loading lever. The frictional force is measured by a frictional force sensor that uses a beam type load cell of 1000 N capacity. Wear is measured in terms of displacement with the help of linear voltage resistance transducer. It is worth noting that, in general wear is measured in terms of wear volume or mass loss. But in the present case, wear is expressed in terms of displacement or wear depth. Hence, to ensure that the wear measurements are accurate, the displacement results for wear are compared with the weight loss of the specimens and almost linear relationship is observed between the two for the range of test parameters considered in the present study. During the experiment the load was changed manually but the speed of the roller and the duration of tests were controlled via a computer attached to the tribotester. To check the repeatability, each test is conducted twice and negligible difference in readings is observed.

2.3 Surface morphology and composition study

Energy dispersive X-ray analysis (EDAX Corporation) is performed to determine the composition of the coating in terms of the weight percentages of nickel phosphorous and tungsten. Figure 3 shows the EDX spectra of the coated surface. The figure ensures the presence of nickel, phosphorous and tungsten. The analysis reveals that the ternary coating consists of 88.57 % nickel, 7.62 % phosphorous and 3.81 % tungsten. Scanning electron microscopy (SEM) (JEOL, JSM-6360) is used to observe the surface morphology.

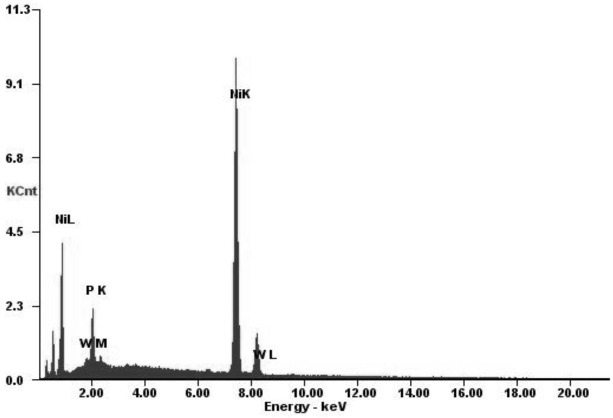
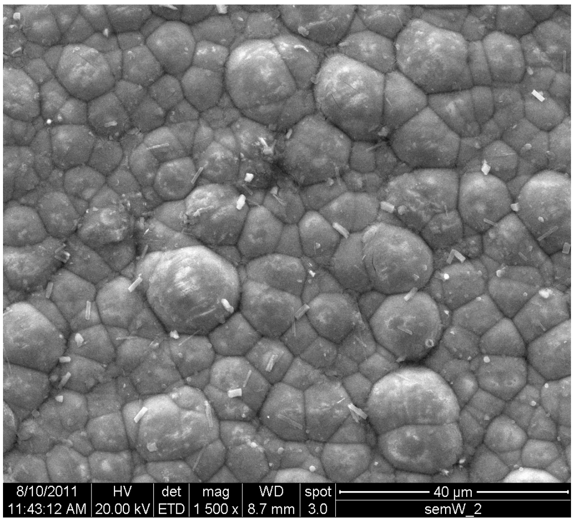
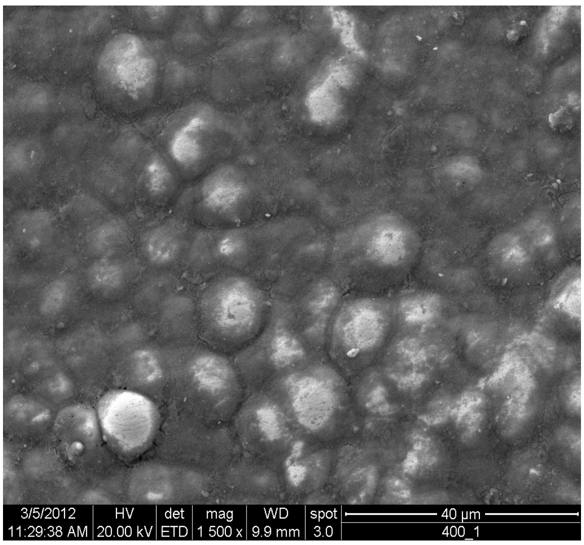


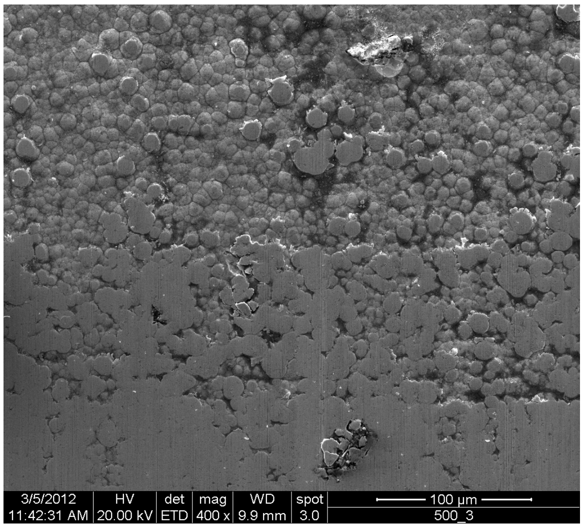
Fig. 3. EDX spectra of Ni-P-W coated surface.



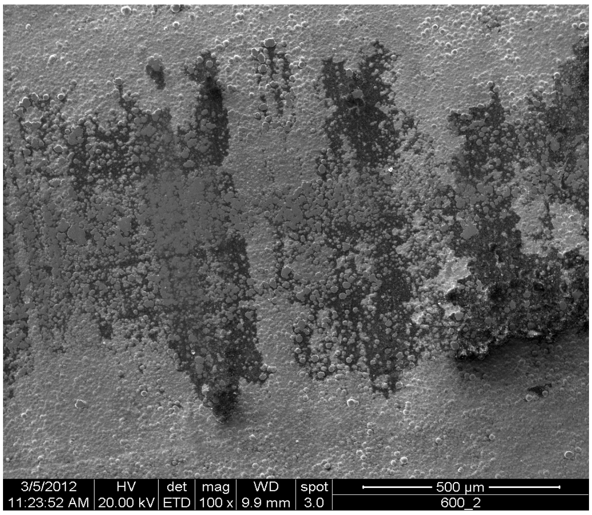
(a)



(b)



(c)



(d)

Fig. 4. SEM image of Ni-P-W coated surface at different conditions (a) as deposited, (b) heat treated, (c) worn surface, (d) wear track.

The SEM image of as deposited, heat treated and the worn surface is shown in Fig. 4. The as deposited image shows that the coated surface has globular spots without any porosity. The heat treated figure shows that after heat treatment the globules become smaller and more compact. From the images of the worn surface it is clear that the load is taken by some of the peak globules where the other peaks remain intact. The wear mechanism is generally mild adhesive in nature because no plowing effect or abrasive particle is observed on the worn surface. Material removal in patches is noticed in SEM images. Moreover, the amount of weight loss of the specimens due to wear corroborates the mild adhesive wear to be predominant. Figure 5 shows the XRD plots of the coatings in as-deposited and heat-treated conditions.

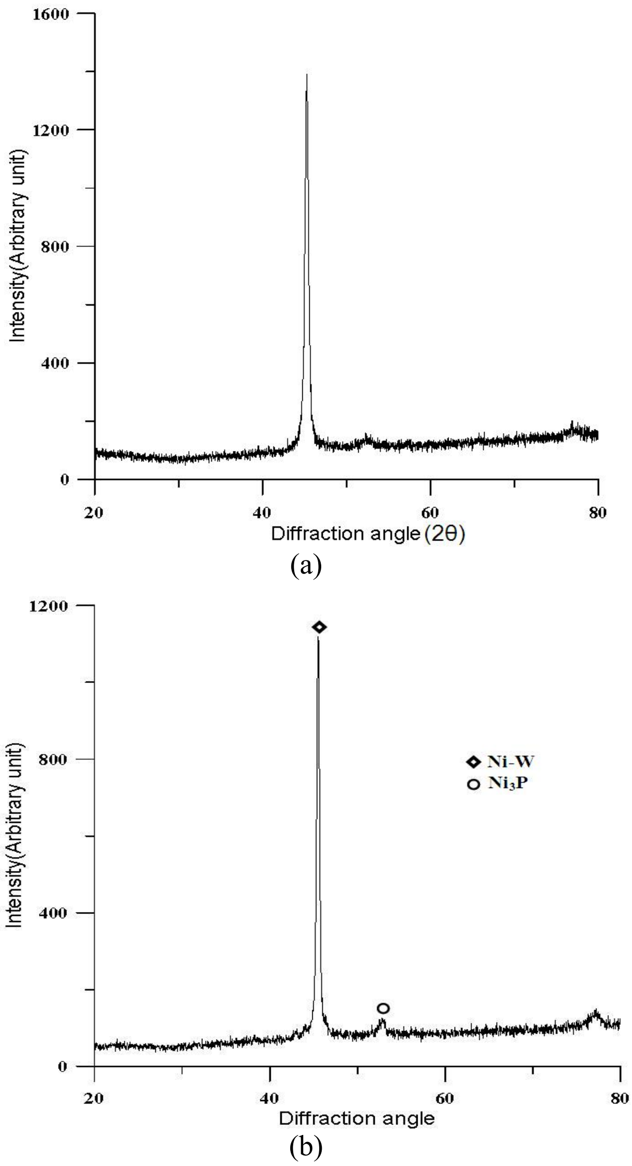


Fig. 5. XRD plots of Ni-P-W coated surface at different conditions, (a) as deposited, (b) heat treated.

From the figure it is seen that in as-deposited condition the phase is mostly amorphous but there exist a crystalline peak. So the coated surface has a mixture of amorphous and crystalline phase. After heat treatment, some of the peaks broaden and produce crystalline phases. The major crystalline peaks are Ni-W and Ni_3P.

3. ANALYSIS METHOD

3.1 Signal to noise ratio

Some measurable responses to the system output during the operation of any engineering system or process are called performance characteristics. These may be applied to the evaluation of the system or process. As the statistical approach of measuring the performance characteristics is more accurate than taking the arithmetic mean, Genichi Taguchi converted the responses in to the signal to noise (S/N) ratio to make an evaluation.

In this study the responses are coefficient of friction and wear depths which are to be minimized for many engineering purpose. Here signal means desirable value (arithmetic mean) and the noise is the undesirable value (standard deviation). A larger S/N ratio represents a better quality characteristic because of the minimization of noise and the corresponding process parameters are incentive to the variation of environmental conditions and other noise factors. The variability can be easily captured if S/N ratio is used to convert the experimental results into a value for the evaluation characteristic in the optimum parameter analysis, instead of the mean.

Table 3. Experimental results and S/N ratio of responses.

EXP. NO.	COF		Wear	
	Value	S/N ratio	Value	S/N rato
1	0.4785	6.402361	6.2982	-15.9843
2	0.46276	6.692883	7.1545	-17.0916
3	0.48203	6.338518	8.055	-18.1213
4	0.39932	7.973578	7.258	-17.2163
5	0.44238	7.08409	8.0496	-18.1155
6	0.44215	7.088607	9.0692	-19.1514
7	0.52605	5.57946	14.164	-23.0237
8	0.54982	5.195589	16.7608	-24.4859
9	0.55751	5.074946	22.0726	-26.8771
10	0.52421	5.609893	10.3106	-20.2657
11	0.55811	5.065603	11.789	-21.4295
12	0.53767	5.389683	14.6806	-23.3349
13	0.48066	6.36324	6.9654	-16.8589
14	0.51542	5.756775	11.114	-20.9174
15	0.56446	4.967336	15.4086	-23.7553
16	0.40976	7.749408	14.8242	-23.4194
17	0.45888	6.766017	17.8212	-25.0187
18	0.44027	7.125618	20.0548	-26.0444
19	0.40823	7.781901	19.9342	-25.992
20	0.46926	6.571729	24.2414	-27.6912
21	0.50418	5.948287	24.8034	-27.8902
22	0.47685	6.432364	11.6952	-21.3602
23	0.51858	5.703684	14.6608	-23.3232
24	0.47967	6.381148	16.5214	-24.3609
25	0.42368	7.45924	16.7828	-24.4973
26	0.52806	5.546334	20.4608	-26.2185
27	0.46618	6.628927	24.7724	-27.8794

The idea is to maximize the S/N ratio, thereby minimizing the effect of random noise factors, which have a significant impact on the process performance. As both the responses i.e., wear depth and coefficient of friction are to be minimized, for this reason the lower-the-better principle is used for the evaluation of product's performance characteristics. The formula is:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Where, y_i is the measured value of responses and n is the number of observations. Table 3 shows the experimental results and corresponding S/N ratios of the responses.

3.2 WPCA method

The principal component analysis (PCA) is a multivariate statistical method that selects a small number of components to account for the variance of original multi-response. The technique was first introduced by Pearson and then further developed by Hotelling [22]. They used a PCA method to transform the normalized multi-response value into uncorrelated linear combinations. Su et al. [23] in their work replaced the original multi-response values with those whose eigenvalue is larger than 1, he also suggested that "trade-off might be necessary to select a feasible solution". Another study by Antony [24] suggested that "the rule of thumb is to choose those components with an eigenvalue greater or equal to one" but there is no further discussion about how to deal with situations where the number of components is bigger than In order to overcome these two main shortcomings in the PCA method, this paper proposes a weighted principal components analysis (WPCA) method. The procedure is described as follows:

Step 1 The original multi-response array for m number of test trials and n number of responses is expressed as:

$$X = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & \cdots & x_2(n) \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ x_m(1) & x_m(2) & \cdots & \cdots & x_m(n) \end{bmatrix} \quad (2)$$

where, x is the S/N ratio of each response.

Step 2 The S/N ratio is normalized using the following formula to get rid of the difference between units.

$$x_i^*(j) = \frac{x_i(j) - x_i(j)_{\min}}{x_i(j)_{\max} - x_i(j)_{\min}} \quad (3)$$

$j = 1, 2, \ldots\ldots$ m.

where, x_i^* is the normalized value of response, $x_i(j)_{\max}$ and $x_i(j)_{\min}$ are the maximum and minimum of $x_i(j)$ respectively.

The normalized multi-response array X^* can be expressed as:

$$X^* = \begin{bmatrix} x_1^*(1) & x_1^*(2) & \cdots & \cdots & x_1^*(n) \\ x_2^*(1) & x_2^*(2) & \cdots & \cdots & x_2^*(n) \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ x_m^*(1) & x_m^*(2) & \cdots & \cdots & x_m^*(n) \end{bmatrix} \quad (4)$$

Step 3 The eigenvalues and eigenvectors are evaluated from the covariance matrix obtained from the normalized data. The covariance matrix is calculated as:

$$A = \begin{bmatrix} \text{variance}(1) & \text{cov}(1,2) & \cdots & \cdots & \text{cov}(1,n) \\ \text{cov}(2,1) & \text{variance}(2) & \cdots & \cdots & \text{cov}(2,n) \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \text{cov}(n,1) & \text{cov}(n,2) & \cdots & \cdots & \text{variance}(n) \end{bmatrix} \quad (5)$$

Then using the equation:

$$[A - \lambda I]*[V] = 0 \quad (6)$$

The eigenvalues (λ) and eigenvector $V = [V_1 \quad V_2 \quad \cdots \quad \cdots \quad V_n]^T$ is computed, imposing the condition $\sum_{i=1}^{n} V_i^2 = 1$.

The eigenvalue, eigenvector and explained variation for this study are shown in Table 4.

Step 4 The principal components are obtained using the following equation

$$Y_{m,n} = X_{m,n}^* \times V_{n,n} \quad (7)$$

Finally the multi-response performance index (MPI) is calculated for jth trial by using the formula:

$$MPI_j = \sum_{i=1}^{n} W_i \times Y_{ij} \quad (8)$$

where, j = 1, 2, ……m.

Here W_i is the proportion of overall variance of the responses explained by i^{th} principal component and Y_{ij} is the i^{th} principal component corresponding to j^{th} trial. Larger value of MPI will imply better quality.

Table 4. Eigenvalue, explained variation and eigenvector for the present study

Principal comp-onent	Eigenvalue	Proportion of explained variation	Eigenvector
First	1.165903	0.58295	[0.707107, 0.707107]
Second	0.834097	0.41705	[0.707107, -0.707107]

The scaled S/N ratio value and the computed MPI for each trial are shown in Table 5. The level averages on the MPI are given in Table 6. As the larger value of MPI indicates better quality, so the optimum combination of process parameters is obtained as A1B2C1 considering the maximum value of level average of each factor.

Table 5. Scaled S/N ratio and MPI values.

EXP. NO.	Scaled value		MPI
	COF	Wear	
1	0.47735	1.00000	0.454847
2	0.57399	0.90700	0.512272
3	0.45611	0.82051	0.418775
4	1.00000	0.89652	0.812279
5	0.70412	0.82100	0.594200
6	0.70562	0.73399	0.585056
7	0.20362	0.40875	0.191930
8	0.07593	0.28594	0.087232
9	0.03580	0.08510	0.035294
10	0.21374	0.64040	0.226264
11	0.03269	0.54265	0.086772
12	0.14049	0.38261	0.144226
13	0.46434	0.92654	0.437028
14	0.26260	0.58566	0.254391
15	0.00000	0.34730	0.040742
16	0.92543	0.37551	0.698431
17	0.59832	0.24118	0.451366
18	0.71793	0.15504	0.525843
19	0.93624	0.15944	0.680726
20	0.53369	0.01672	0.379335
21	0.32630	0.00000	0.230732
22	0.48733	0.54847	0.408935
23	0.24494	0.38360	0.218199
24	0.47029	0.29643	0.367322
25	0.82891	0.28498	0.619559
26	0.19260	0.14042	0.152660
27	0.55271	0.00091	0.390935

Table 6. Level averages on MPI.

Level	A	B	C
1	0.4102	0.3482	0.5033
2	0.3183	0.4131	0.304
3	0.3832	0.3504	0.3043
Delta	0.0919	0.0649	0.1993
Rank	2	3	1

3.3 Analysis of variance (ANOVA)

Analysis of variance is carried out on the MPI values shown in Table 7. The result reveals that among all the three factors the time (C) and among the interactions the interaction between load (A) and speed (B) is most significant for controlling the friction and wear behaviour.

Table 7. ANOVA on MPI

Sou-rce	Dof	Sum of square	Mean of square	F-ratio	% contri-bution
A	2	0.04012	0.02006	1.58	3.31
B	2	0.02447	0.01224	0.96	2.02
C	2	0.23796	0.11898	9.34*	19.62
A*B	4	0.74332	0.18583	14.59*	61.28
A*C	4	0.0421	0.01052	0.83	3.47
B*C	4	0.02326	0.00581	0.46	1.92
Error	8	0.10186	0.01273		8.40
Total	26	1.21308			100.00
* 99 % significant $F_{0.01, 2, 8}$ = 8.65, $F_{0.01, 4, 8}$ = 7.01					

4. CONFIRMATION TEST

A confirmation test is carried out in order to validate the result. A comparison between the initial parameter combination and optimum combination is shown in Table 8.

Table 8. Results of confirmation test.

Responses	Initial combination	Optimum combination	% improvement
	A2B2C2	A1B2C1	
COF	0.51542	0.39932	22.5
Wear depth	11.114	7.258	34.69
Total S/N ratio	-15.160632	-9.242761	39
Improvement of S/N ratio = 5.917871 dB			

From the table it is clear that the total S/N ratio of optimum combination is higher than the initial parameter combination. It is well known that regardless of the category of the performance characteristics, a higher S/N ratio always corresponds to a better performance. Hence the result of confirmation test ensures the better performance of the optimum design.

5. CONCLUSION

In the present study weighted principal component analysis (WPCA) is used to optimize the tribological process parameters (load, speed and time) together in order to optimize coefficient of friction and wear depth of Ni-P-W coating. The optimal combination of coating parameters is obtained as A1B2C1. ANOVA result indicates that time (C) is the most important parameter that significantly affects the tribological characteristics at a confidence level of 99 %. Also the interaction between load and speed is significant at the same level of confidence. The improvement of the S/N ratio from the initial condition to the optimal condition is observed. From the EDX analysis it is clear that the coating is pure ternary and consists of nickel, phosphorous and tungsten. From the surface morphology captured by SEM it is seen that there are many globular particles on the surface of the substrate with no surface damage. Also the coating is dense and with low porosity and the worn surface shows the wear is mild adhesive in nature. The XRD plots reveal that the coating is a mixture of amorphous and crystalline structure in the as-deposited condition and produce Ni-W and Ni_3P as major compounds after heat treatment.

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