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APPLICATION OF TAGUCHI METHOD AND GREY RELATIONAL ANALYSIS IN THE OPTIMIZATION OF COATING PARAMETERS FOR SURFACE ROUGHNESS IN ELECTROLESS NI-P COATING

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ABSTRACT

Surface roughness is used to evaluate the quality of a product. This paper presents an approach based on the Taguchi method with the grey relational analysis for optimizing process parameters in electroless Ni-P coating for surface roughness with multiple performance characteristics. A grey relational grade obtained from the grey relational analysis is used to solve the deposition of electroless Ni-P coating. The optimal coating parameters can then be determined by the Taguchi method using the grey relational grade as the performance index. For this purpose, analyses are carried out by utilizing the combination of process parameters based on L_{27} Taguchi orthogonal design. The signal-to-noise (S/N) ratio and the analyses of variance (ANOVA) are used to find the optimum levels and to indicate the impact of the process parameters on surface roughness. Also, various surface roughness parameters such as centre line average (R_a), root mean square (R_q), skewness (R_{sk}), kurtosis (R_{ku}) and mean line peak spacing (R_{sm}) are evaluated.

Keywords: ANOVA, EN coating, Surface roughness, Taguchi method, grey relational analysis.

1. INTRODUCTION

Electroless Ni-P (EN) coating is an autocatalytic deposition of a NiP alloy from an aqueous solution unto a substrate without the application of electric current. The electroless bath typically comprises an aqueous solution of metal ions, complexing agents, reducing agents and stabilizers, operating in a specific metal ion concentration, temperature and pH ranges. The deposition rate, properties of coated components and the structural behavior of deposits mainly depend upon the plating bath constituents/conditions such as the type and concentrations of the reducing agent, stabilizer, used pH and the temperature of the bath etc. [1]. Eletroless deposition process therefore differs from the conventional electroplating processes that depend on an external source of direct current in order to reduce nickel ions in the electrolyte to nickel metal on the substrate. EN coatings have got wide range of industrial applications because of their excellent mechanical, electrical, physical, corrosion, hardness, friction and wear resistance properties. Other outstanding characteristics of EN coatings include the ability to be applied to a variety of substrate material and the ability to plate uniformly on intricate part geometries [2]. In case of EN coatings, the mechanism behind the formation of the surface roughness is very complicated and process dependent [3]. Substrate surface morphology and its metallurgical condition affect the quality of EN coatings. The porosity of EN coatings has been found to depend not only on their surface roughness but also on their surface morphology [4-6]. Wear and friction are also strongly affected by surface roughness and so an optimum surface roughness can be found out which will provide a minimum wear and friction and at the same time a better quality product with respect to surface roughness value [7]. So it is an important task to select the suitable coating parameters for getting better surface quality.

The effects of substrate surface roughness and coating thickness on the properties of EN coatings were studied by Ernst et al. [8]. On very smooth substrate surfaces the R_a value increases whereas on rough surfaces the applications of EN coatings tend to decrease R_a values. It has been seen that the substrate R_a parameter remains practically unchanged irrespective of the EN coating thickness. EN coating follows the profile of the substrate surface waviness rather than filling it up as usually obtained in conventional electroplating [1]. In the electroless plating process, many factors affect the relation between the surface roughness and coating thickness such as plating temperature, plating time, pH value of plating solution and so on [9]. It has been seen that in case of composite coatings like NiP-TiO_2, have higher roughness values than comparing to plain Ni-P coating [10]. However, all these studies whether experimental or analytical mostly concentrate on the centre line average roughness value for surface quality. A surface generated is composed of a large number of length scales of superimposed roughness [11] and thus consideration of centre line average roughness alone is not sufficient to describe the surface quality. The present study aims at consideration of five different roughness parameters, viz. centre line average roughness (R_a), root mean square roughness (R_q), skewness (R_{sk}), kurtosis (R_{ku}) and mean line peak spacing (R_{sm}) for the surface texture generated in Electroless Ni-P coating on mild steel specimens. It is difficult to consider all the factors that affect the surface finish in any experimental study. In the present study, by varying three coating parameters, viz. bath temperature (*A*), reducing agent (*B*) and source of metallic ions (*C*) attempts have been made to evaluate effect of process parameter on surface roughness parameters. This present study deals with the application of the Taguchi method with grey relational analysis to determine the suitable coating process parameters in order to study and optimize surface roughness in electroless Ni-P coating.

2. TAGUCHI DESIGN METHOD

The Taguchi technique [12] is a powerful tool for design of high quality systems based on orthogonal array experiments that provide much reduced variance for the experiments with an optimum setting of process control parameters. This method achieves the integration of design of experiments (DOE) with the parametric optimization of the process yielding the desired results. The orthogonal array (OA) requires a set of well balanced (minimum experimental runs) experiments. In this method, main parameters, which are assumed to have an influence on process results, are located at different rows in a designed orthogonal array. With such an array, completely randomized experiments can be conducted. Taguchi's method uses the statistical measure of performance called signal–to-noise ratios (S/N), which are logarithmic functions of desired output to serve as objective functions for optimization. The ratio depends on the quality characteristics of the product/process to be optimized. The three categories of S/N ratios are used: lower-the-better (LB), higher-the-better (HB) and nominal-the-best (NB). The parameter level combination that maximizes the appropriate S/N ratio is the optimal setting.

3. GREY RELATIONAL ANALYSIS

The present study aims at optimizing five roughness parameters of EN coatings. Thus it is a case of multi response optimization which is different from that of a single performance characteristic. The higher S/N ratio for one performance characteristic may correspond to a lower S/N ratio for another. Therefore, the overall evaluation of the S/N ratio is required for the optimization of multiple performance characteristics. Grey relational analysis [13] is an efficient tool for such multi response analysis. Grey relational analysis owes its origin to grey system theory. Any system in nature is not white (full of precise information), but on the other hand, it is not black (completely lack of information) either, and it is mostly grey (a mixture of black and white). The incompleteness of information is the basic characteristic and it serves as the fundamental starting point of the investigation of grey system. Incomplete information follows from the limited availability of data and the central problem of grey system theory is to seek only the intrinsic structure of the system given such limitation of data. The main objective of grey system theory is to supply information so that one can whiten the greyness. Grey relational analysis is based on the grey system theory, and compares and computes the dynamic causalities of the subsystems of a given system.

In grey relational analysis the first step is to perform the grey relational generation in which the results of the experiments are normalized in the range between zero and one. Then the second step is to calculate the grey relational coefficient from the normalized data to represent the correlation between the desired and actual experimental data. The overall grey relational grade is then computed by averaging the grey relational coefficient corresponding to each performance characteristic. Overall evaluation of the multiple performance characteristics is based on the calculated grey relational grade. As a result, optimization of the complicated multiple performance characteristics is converted into optimization of a single grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade. Furthermore, a statistical analysis of variance (ANOVA) [14] is performed to find which process parameters are statistically significant. With the grey relational analysis and statistical analysis of variance, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the analysis.

4. EXPERIMENTAL DETAILS

Mild steel specimens are used as the substrate material for the deposition of the electroless Ni-P coating. Square shaped specimens are prepared very carefully for the deposition of the electroless Ni-P coating. Shaping, parting and milling processes are used accordingly for the preparation of the samples. The samples are then finally subjected to surface grinding process. Then the samples are mechanically cleaned from foreign matter and corrosion products. After that surfaces of the mild steel specimens are cleaned using distilled water. The specimens, after thorough cleaning are given a pickling treatment with dilute hydrochloric acid for one minute. Subsequently, they are rinsed in distilled water followed by methanol cleaning prior to coating.

The compositions and operating conditions for electroless Ni-P coating are selected after several experiments and proper ranges of the parameters are chosen accordingly. Three most important parameters are varied and others are kept constant. Table 1 indicates the composition and operating conditions used for the deposition of electroless nickel phosphorus coating. The input parameters chosen for the experiment were I) bath temperature II) sodium hypophosphite and III) nickel chloride and nickel sulphate. Table 2, indicates the factors and their levels.

Table 1: Composition and operating conditions of Ni–P plating bath

Bath Composition		***Operating conditions***	
Nickel Sulphate/Nickel Chloride (g/l)	30 to 50	pH Time	4.5 2 hr
Sodium Hypophosphite (g/l)	10 to 24	Deposition Temp.(ºC)	80 to 90
Sodium Succinate (g/l)	12	Bath vol. (ml)	175

Table 2: Coating parameters and their levels

Variables	*Units*	*Levels*		
		1	2	3
(A)	^{0}C	80	85[a]	90
(B)	g/l	10	17[a]	24
(C)	g/l	30	40[a]	50

a initial coating condition

Now an orthogonal array is employed to reduce the number of experiments for determining the optimal coating process parameters. In the present investigation, an L_{27} orthogonal array is chosen. In the Taguchi orthogonal array, the 1st column is assigned to bath temperature (A), 2nd column is assigned to sodium hypophosphite (B) and 5th column is assigned to nickel chloride and nickel sulphate (C) and the remaining columns are assigned to their interactions. Besides the influences of control factors, the influence of their interactions on the surface roughness of the electroless nickel phosphorus coating are studied as well. The S/N ratio for each level of process parameters is computed based on the S/N analysis. The response to be studied is the surface roughness with the objective of smaller is the better. Moreover, a statistical analysis of variance is performed to see which parameters are statistically significant. The orthogonal array design may be found elsewhere [15].

Electroless coating is carried out using nickel chloride and nickel sulphate as the source of nickel, sodium hypophosphite as the reducing agent and sodium succinate as the stabilizer. The concentration of stabilizer used in baths is kept fixed. The pH value of the baths was maintained at a fixed value by adding required quantity of dilute hydrochloric acid. The activation temperature has been kept constant at 55 ºC The cleaned samples have been activated in palladium chloride at 55 ºC temperature and placed in the bath for deposition for 2 hours. Deposition time was kept constant for each and every specimen so that the coating thickness is constant. 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. Each and every specimen is coated and heat treated separately according to the orthogonal array.

The surface roughness parameters has been measured with a stylus profilometer, Talysurf (Taylor Hobson, Surtronic 3+) using a 0.8 mm sampling length and 4 mm traversing length. Roughness measurements on the coated samples have been repeated at least four times and average of four surface roughness parameter values was recorded. Table 3 shows the experimental results of various surface roughness parameters.

Table 3: Experimental results of surface roughness parameters

Exp. Nos.	R_a (μm)	R_q (μm)	R_{sk}	R_{ku}	R_{sm} *(mm)*
1	0.40450	0.6020	0.4068	4.6525	0.1940
2	0.44250	0.5250	0.9495	5.0000	0.1010
3	0.43350	0.6630	0.5373	4.9675	0.0790
4	0.30930	0.3490	0.8788	5.3500	0.1860
5	0.44600	0.5110	0.9163	5.1575	0.0694
6	0.41700	0.5030	0.6087	4.7900	0.1140
7	0.33200	0.4020	1.1035	7.8225	0.1130
8	0.33425	0.4870	0.6213	7.3650	0.1740
9	0.48200	0.5530	1.0193	7.6150	0.0503
10	0.47400	0.5350	0.4073	3.9900	0.1870
11	0.66450	0.7690	0.8605	5.1825	0.0763
12	0.50075	0.6420	1.2360	4.5333	0.1630
13	0.36375	0.4570	0.5047	6.5533	0.1600
14	0.41950	0.5890	1.3765	6.3600	0.1120
15	0.38425	0.4220	0.3493	3.8950	0.1330
16	0.32525	0.4710	2.3260	5.5575	0.1650
17	0.50800	0.5910	0.7280	5.8275	0.1300
18	0.40150	0.4790	1.6333	9.5150	0.1150
19	0.33075	0.3990	0.3705	4.1550	0.1870
20	0.35275	0.5000	0.9860	6.5100	0.1060
21	0.37875	0.4610	0.7670	5.6775	0.1290
22	0.45800	0.5100	0.5350	4.0500	0.1380
23	0.40750	0.5120	0.6620	6.0700	0.1180
24	0.43775	0.6110	0.6930	5.7733	0.0950
25	0.47325	0.5980	0.8970	6.7900	0.1070
26	0.45800	0.5340	0.8870	5.9675	0.1130
27	0.28725	0.3640	1.2400	7.666	0.1600

5. GREY RELATIONAL ANALYSIS FOR ELECTROLESS NI-P COATING

In this grey relational analysis, the normalized data processing for corresponding to lower- the-better criterion can be expressed as

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

and the normalized data processing for corresponding to higher- the-better criterion can be expressed as

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

Where $x_i(k)$ is the value after the grey relational generation, min $y_i(k)$ is the smallest value of y_i (k) for the kth response, and the max $y_i(k)$ is the largest value of the $y_i(k)$ for the kth response. An ideal sequence is $x_0(k)$ (k=1, 2… 27). The definition of grey relational grade in the grey relational analysis is to show the relational degree between the twenty seven sequences [$x_0(k)$ and $x_i(k)$, i=1,2;3; k=1, 2, …., 27].The grey relational coefficient ξ_i *(k)* can be calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{oi}(k) + \xi \Delta_{\max}}$$, Where

$\Delta_{0i} = \|x_o(k) - x_i(k)\|$ = difference of the absolute value between $x_0(k)$ and $x_i(k)$; ξ =distinguishing coefficient in between zero and one.

$\Delta_{\min} = \forall j^{\min} \in i \forall k^{\min} \|x_o(k) - xj(k)\|$ = the smallest value of Δ_{0i} ; and

$\Delta_{\max} = \forall j^{\max} \in i \forall k^{\max} \|x_o(k) - xj(k)\|$ = largest value of Δ_{0i} .The grey relational coefficient results for the experimental data are shown in the Table 4. After averaging the grey relational coefficients, the grey relational grade γ_i can be calculated as follows:

$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$, where n = number of process responses.

Table 4. Grey relational coefficient of each performance characteristics

Exp. Nos.	R_a (μm)	R_q (μm)	R_{sk}	R_{ku}	R_{sm} *(mm)*
1	0.6167	0.4536	0.9450	0.7876	0.3333
2	0.5485	0.5441	0.6222	0.7178	0.5863
3	0.5633	0.4008	0.8402	0.7238	0.7146
4	0.8954	1.0000	0.6511	0.6588	0.3462
5	0.5430	0.5645	0.6355	0.6900	0.7900
6	0.5925	0.5769	0.7921	0.7584	0.5301
7	0.8083	0.4413	0.5672	0.4171	0.5340
8	0.8005	0.6034	0.7842	0.4475	0.3674
9	0.4920	0.5073	0.5960	0.4303	1.0000
10	0.5024	0.5303	0.9446	0.9673	0.3445
11	0.3333	0.3333	0.6591	0.6858	0.7343
12	0.4691	0.4175	0.5271	0.8149	0.4222
13	0.7114	0.6604	0.8642	0.5139	0.3958
14	0.5878	0.4667	0.4903	0.5327	0.5380
15	0.6604	0.7421	1.0000	1.0000	0.4649
16	0.8324	0.6325	0.3333	0.6283	0.3851
17	0.4607	0.4646	0.7230	0.5925	0.4741
18	0.6228	0.6177	0.4349	0.3333	0.5262
19	0.8126	0.8071	0.9790	0.9152	0.3445
20	0.7423	0.5817	0.6082	0.5180	0.5633
21	0.6734	0.6521	0.7029	0.6118	0.4772
22	0.5249	0.5661	0.8427	0.9477	0.4503
23	0.6106	0.5630	0.7596	0.5637	0.5149
24	0.5562	0.4449	0.7419	0.5994	0.6164
25	0.5035	0.4575	0.6434	0.4926	0.5589
26	0.5249	0.5316	0.6477	0.5755	0.5340
27	1.0000	0.9334	0.5260	0.4270	0.3958

The higher the value of grey relational grade considered as the stronger relational degree between the ideal sequence $x_0(k)$ and the given sequence $x_i(k)$. Earlier it has mentioned, the ideal sequence $x_0(k)$ is the best process response in the experimental layout. Here, it may conclude, the higher relational grade means that the corresponding parameter combination is closer to the optimal. Table 5 shows the experimental results for the grey relational grade and their order.

Table 5. Grey relational grade and its order

Exp. No.	*Grey relational grade*	*Order*
1	0.62724	11
2	0.60378	14
3	0.64854	8
4	0.71030	3
5	0.64460	9
6	0.65000	7
7	0.55358	21
8	0.60060	17
9	0.60512	13
10	0.65782	5
11	0.54916	22
12	0.53016	25
13	0.62914	10
14	0.52310	26
15	0.77348	1
16	0.56232	20
17	0.54298	23
18	0.50698	27
19	0.77168	2
20	0.60270	15
21	0.62348	12
22	0.66634	4
23	0.60236	16
24	0.59176	18
25	0.53118	24
26	0.56274	19
27	0.65644	6

6. ANALYSIS OF SIGNAL TO NOISE RATIO

The traditional method of calculating the desirable factor levels is to look at the simple averages of the results. But it does not capture the variability of the results within a trial condition. That's why the signal to noise ratio analysis is done here with the grey relational grade as the performance index. To obtain better surface quality, the centre line average (R_a) is to be of minimum value. For this case, lower-the-better quality characteristics are considered. Similarly, for root mean square (R_q) roughness value lower-the-better quality characteristics are considered. The skewness (R_{sk}) roughness value, for a symmetrical distribution like Gaussian distribution, is to be zero i.e, (R_{sk}=0).The data collected in experimentation, all are of positive skewness. For optimal surface roughness lower-the-better quality characteristics have been taken into consideration. Furthermore, the kurtosis (R_{ku}) value for Gaussian distribution is 3 (three). So, for this case also the lower the better quality characteristics have been taken into consideration. Again, for mean line peak spacing, R_{sm}, lower - the - better quality characteristic is considered.

The response table for this analysis is shown below in Table 6. The corresponding main effects plot of the process parameters are shown in Fig. 1. It is very much clear from the main effects plot that parameter B is the most significant parameter among the all other parameters.

Table 6. Response table of Grey relational grade

Level	*A*	*B*	*C*
1	0.627084	0.623840	0.634400
2	0.586127	0.643453	0.581336
3	0.623187	0.569104	0.620662
Rank	3	1	2
Delta	0.040958	0.074349	0.053064

The total mean grey relational grade = 0.61213dB

From the signal to noise ratio analysis and the main effects plot it is clear that the most significant parameter is the reducing agent for the resulting surface roughness parameters. The suitable coating parameter combination found from the main effects plot is parameter A at level 1, parameter B at level 2 and parameter C at level 1, i.e. A1B2C1.

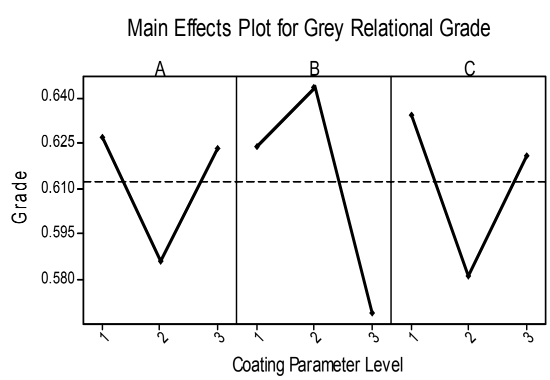

Fig 1: Main effects plot for Grey Relational Grade

7. ANALYSIS OF VARIANCE (ANOVA)

The idea of the analysis of variance is to find out the significance of process parameters on surface roughness. This is accomplished by separating the total variability of the S/N ratio, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. The percentage contributions of variance can be calculated by using the following equations.

The total sum of square deviations SS_T from the total mean of the S/N ratio (η_n) can be evaluated as follows:

$SS_T = SS_d + SS_e$

$$SS_T = \sum_{i=1}^{m} (\eta_i - \eta_n)^2$$

$$= \sum_{i=1}^{m} \eta_i^2 - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_i\right]^2$$

Where, m is the number exeperiments in the orthogonal array and η_i is the mean S/N ratio for the ith experiments.The percentage of contributions ρ can be calculated as follows:

$$\rho = \frac{SS_d}{SS_T}$$

Where, SS_d is the sum of the square deviations and SS_e is the sum of squared error. In the statistical analysis, F - tests are carried out to see which design parameters have a significant effect on the surface characteristics. To conduct the F - test the mean of the square deviations SS_m due to each design parameter needs to be calculated.

$$SS_m = \frac{\text{Sum of squared deviations}(SS_d)}{\text{Number of degrees of freedom of each parameters}}$$

F- value can be found out with following equation:

$$\text{F- value} = \frac{\text{Mean squared deviation}(SS_m)}{\text{Mean squared error}(SS_e)}$$

F ratio in calculation of three process parameters is analysed from the table as $F_{0.25,2,6}$=1.76 and $F_{0.25,4,6}$=1.79. Usually, when $F_{calculated} > F_{tabulated}$, it means that the change of the process parameter has a significant effect on the quality characteristics. Generally when F value increases the significant of the parameter also increases. Table 7 shows the analysis of variance table for surface roughness.

Table 7. ANOVA Analysis for grey relational grade

Source	*DF*	*SS*	*MS*	*F*	*% P*
A	2	0.009199	0.004599	0.93	7.5
B	2	0.026725	0.013363	2.69*	22
C	2	0.013653	0.006827	1.38	11
A*B	4	0.010180	0.002545	0.51	8
A*C	4	0.004150	0.001037	0.21	3
B*C	4	0.019183	0.004796	0.97	15.5
Error	6	0.039689	0.004951		
Total	26	0.122779			

* - significant at 75% confidence level

From the ANOVA analysis it is clear that the parameter B has got a significant amount of percentage contribution (22%). But neither of the parameters is found to be significant for the resulting surface roughness of EN coating. However, only the parameter B is found to be significant at the confidence level of 75%. But neither of the parameters is found to be significant at higher level of confidence. All other parameters and interactions are negligible. This is due to the reason that EN coating strictly follows the subsurface morphology. In general, the roughness of EN coatings increased with the initial substrate roughness. EN coatings do not subvert the roughness of substrate therefore the coating thickness does not effect the resulting surface roughness substantially. This actually indicates that the substrate roughness remains practically unchanged irrespective of the EN coating thickness. Similar results are also obtained from this study as the signal to noise ratio analysis and ANOVA shows that the coating process parameters do not have any significant effect for the resultant roughness. It simply follows the subsurface profile. So, these results are well established with the earlier literatures like Taheri et al [1]. The above results suggest that EN coatings do not necessarily seal off the substrate asperities. Rather, it follows the surface morphology of the substrate material. So, it can be said that the roughness of substrate and the EN coating are practically identical. If the roughness of substrate increases than resulting EN coating roughness also increases and vice versa. So, the results obtained in this experiment are in good agreement with the earlier established results.

8. CONFIRMATION TEST

After the optimal level of process parameters has been found out, a verification test is to be carried out in order to control the accuracy of analysis. The estimated grey relational grade $\hat{\eta}$,using the optimal level of the process parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o} \left(\overline{\eta}_i - \eta_m \right)$$

where η_m is the total mean grey relational grade, $\overline{\eta}_i$ is the mean grey relational grade at the optimal level, and o is the number of the main design parameters that significantlly affect the surface roughness characteristics of electroless Ni-Pcoating.

Table 8. Results of confirmation test

	Initial parameter	**Optimal parameter**	**Exp.**
Level	A2B2C2	A1B2C1	
R_a	0.4195		0.3093
R_q	0.5890		0.3490
R_{sk}	1.3765		0.8788
R_{ku}	6.3600		5.3500
R_{sm}	0.1120		0.1860
Grade	0.5231	0.643453	0.7103

Improvement of grey relational grade = 0.18720

Table 8 shows the comparison of the estimated grey relational grade with the actual grey relational grade using the optimal parameters that good agreements between the estimated and actual grey relational grade is taking place. The improvement of grey relational grade from initial to optimal condition is 0.18720.

9. CONCLUSIONS

The use of Taguchi method and grey relational analysis to optimize the electroless Ni-P coating with multiple performance characteristics has been presented in this paper. It can be concluded from the above analysis that the coating process parameters are not significant at 95% confidence level for the resulting surface roughness. It proves that EN coating strictly follows the subsurface morphology. The surface roughness of EN coating is dependent on substrate roughness. If substrate roughness is more, then the resulting EN coating roughness will be more and vice versa. That's why it can also be said that EN coating thickness does not have any effect on the roughness. All these conclusions are well established with earlier research work. However, considering the reducing agent as the most significant parameter as obtained from the ANOVA analysis at the confidence level of 75% a suitable parameter combination of the coating process parameters is obtained which gives optimum surface roughness. From signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA), the optimal process parameter combination for resulting surface roughness is found to be A1B2C1. It is also seen that the improvement of grey relational grade from initial to optimal process parameter condition is 0.18720.

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