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Fractal Dimension Optimization of Electroless Ni-P-Cu Coatings Using Artificial Bee Colony Algorithm

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Abstract

The paper describes an experimental study for determination of fractal dimension of electroless Ni-P-Cu coatings and its optimization using artificial bee colony algorithm. Experiments are conducted based on face centre cubic response surface methodology experimental design considering variation in three process parameters, namely concentration of nickel source solution, concentration of reducing agent and concentration of copper sulphate solution. The variation of fractal dimension with process parameters is studied. The optimum values of each coating process parameters are obtained from the analysis and the corresponding value of fractal dimension is also obtained. The surface morphology and composition of coatings are also studied with the help of scanning electron microscopy, energy dispersed x-ray analysis.

Keywords

Electroless, Ni-P-Cu, Fractal Dimension, Optimization, ABC Algorithm

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1. Introduction

Electroless nickel (EN) plating is undoubtedly the most important catalytic plating process in use today. The principal reasons for its widespread commercial and industrial use are to be found in the unique properties of the EN deposits. The chemical and physical properties of an EN coating depend on its composition, which, in turn, depends on the formulation and operating conditions of the EN plating bath [1, 2]. Among them the binary electroless nickel phosphorous (Ni-P) coating get widespread popularity due to its simplicity and excellent properties. The recent studies confirmed that inclusion of Cu into Ni-P coatings improves their thermal stability, brightness, and corrosion resistance and can reduce the fatigue properties of the substrate. Thanks to these properties, for which this type of coatings are used as alternatives in various significant fields like bio-engineering, aerospace, automotive design and manufacture. A typical use of this type of coatings is on the missile components, because the missiles are assembled at the launch pads which are generally located at marine atmosphere. So there is a great chance that the components may get damaged due to corrosion. It can be prevented by applying electroless Ni-P-Cu coating as it has a very good anti-corrosive property which has been proven by many researchers [4-9]. But when the missile passes through the atmosphere the components experience a huge frictional force due to its rough surface. So for safety the surface should be smooth enough for minimizing the frictional force. Hence surface roughness plays an important role in this purpose.

Conventionally the surface roughness is the deviation of surface from the mid plane which can be expressed by different statistical parameters like variances of height, the slope, curvature etc [10]. But these characteristics are strongly dependent on the resolution of the roughness measuring instrument. Hence instruments with different resolutions and scan lengths yield different values of these

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statistical parameters for the same surface. The difficulty with the conventional methods is that although rough surfaces contain roughness at a large number of lengths of scales, the characterization parameters depend only on a few particular length scales, such as the instrument resolution or the sample length. A logical solution to this problem is to characterize rough surfaces with a scale-invariant parameter such as fractal dimension. The multi-fractal spectra of Ni-P-Cu coating have been studied by Yu et al. [11].

The fractal dimension of electroless coated surface is basically dependent on the coating parameters and operating conditions. This research is focused to find out the optimum combination of coating process parameters within a given range for better fractal dimension. In this study the investigation of the optimum combination of coating process parameters for a larger value of fractal dimension artificial bee colony (ABC) algorithm is employed. There are so many evolutionary optimization processes like GA, PSO etc, but according to recent studies [12], ABC algorithm can be employed to any unconstrained problem with less number of control parameters and gives better performance than the other similar type population based algorithm. The performance of ABC algorithm on clustering is compared with the result of the PSO algorithm by Karaboga et al. [13], and according to them both the algorithms drop in the same class of artificial intelligence optimization algorithms. The surface morphology and composition of the coatings are studied with the help of scanning electron microscopy (SEM) and energy dispersed x-ray analysis (EDX).

2. Fractal Characterization

Most rough surfaces including machining ones and corresponding profiles are multi-scale in nature. This multi-scale property is better expressed as self-similarity or self-affinity in fractal geometry implying that when the surface or the profile is magnified more and more details emerge and the magnified image is statistically similar to the original topography [14]. Statistical self-similarity means that the probability distribution of a small part of a profile will be congruent with the probability distribution of the whole profile if the small part is magnified equally in all directions. On the other hand, self-affinity implies unequal scaling in different directions. The property of self-affinity can be characterized by the profile fractal dimension D ($1 < D < 2$). In this paper, isotropic and homogeneous rough engineering surface of dimension D_s ($2 < D_s < 3$) is considered. The property of isotropy means that the probability distribution of heights is invariant when the coordinate axes are rotated and the surface is reflected on any plane.

The property of homogeneity of a surface indicates that the probability distribution of the height is independent of the location on the surface [15]. Therefore, the profile, z(x), of such a surface along a straight line and in any arbitrary direction is of dimension $D = D_s - 1$ and is a statistically valid representation of the surface. Thus the profile fractal dimension D is adopted to characterize the fractal nature of the surface in this paper [16]. These properties are satisfied by the Weierstrass–Mandelbrot (W–M) fractal function, which can be used to characterize the roughness of the surface profile and is given as

$$Z(x) = G^{(D-1)} \sum_{n=n_1}^{\infty} \frac{\cos 2\pi\gamma^n x}{\gamma^{(2-D)n}}, 1 < D < 2; \gamma > 1 \quad (1)$$

where G is a characteristic length scale and $\gamma^{n1} = 1/L$ where L is the sampling length. $\gamma^n = \omega$, where frequency ω is the reciprocal of the wave length and n is called the wave number. To provide both phase randomization and high spectral density, γ is selected to be 1.5. The parameters G and D form the set to characterize profile z(x). The methods for calculating profile fractal dimension mainly include the yard-stick, the box counting, the variation, the structure function and the power spectrum methods. The power spectrum, $S(\omega)$ of the W–M function is given as

$$S(\omega) = \frac{G^{2(D-1)}}{2 \ln \gamma} \frac{1}{\omega^{(5-2D)}} \quad (2)$$

The structure function $S(\tau)$ of the sampling data on the profile curve z(x) can be described as [17]

$$S(\tau) = \left\langle [Z(x+\tau) - Z(x)]^2 \right\rangle = C\tau^{(4-2D)} \quad (3)$$

where τ is any displacement along the x direction, $\langle \ \rangle$ is the temporal average and C is a constant. In comparison with the power spectrum method, the structure function is more exact and easy to operate. For this reason the structure function method is adopted to characterize the fractal character of the surface profiles in this paper. Hence D can be determined from the structure function plot on log–log coordinates. The physical significance of D is the extent of space occupied by the rough surface, i.e. larger D values correspond to a denser profile or smoother topography.

3. Artificial Bee Colony (ABC) Algorithm

Inspired by the intelligent foraging behavior of honey bees, Karaboga [12] introduced the ABC algorithm for optimizing numerical problems. Since the present study uses ABC algorithm for optimization of fractal dimension of electroless coating, it is felt necessary to explain the salient features of the algorithm in a nutshell. It can be noted that three parameters are of prime importance in the foraging behavior of honey bees, those are, food source (nectar), employed foragers and unemployed foragers, and the foraging behavior leads to two modes, i.e., recruitment of nectar source and abandonment of nectar source. In ABC, the colony of artificial bees contains generally two groups of bees: employed bees and onlooker bees. The employed bees have all the idea about the food source (nectar position) and quality of food (nectar amount). In the hive all the employed bees with all their information of foods started waggle dance. This dance is the indication of all the characteristics of their foods, i.e., the amount as well as quality of foods. In the hive there are also some unemployed bees called onlooker bees. They watch the waggle dance and get the information about all the food sources and attracted to the best food source. In the next stage the onlooker bees become employed and they started consuming the nectar from the best food source. When this food source becomes abandoned the employed bee become a scout bee and starts to find new food source. As early as a scout finds a new food source it becomes an employed bee and the cycle goes on until the best food source (optimum solution) is obtained.

In the initialization step the algorithm generates randomly distributed predefined number of initial food source (solution). Since each food source Xi is a solution vector to the optimization problem, each X_i vector holds n variables, (X_{ij}, j = 1…n) which are to be optimized. After initialization, the solutions is subjected to repeated cycles C = 1…MCN (maximum cycle number). This is for the search process of the employed bees, onlooker bees and scout bees. In the next step i.e., employed bees phase the employed bees search for new food sources (V_{ij}) having more nectar within the neighborhood of the food source (X_{ij}) in their memory. They find a neighbor food source and then evaluate its profitability (fitness). The neighbor food source (V_{ij}) is determined by using the formula given by:

$$v_{ij} = x_{ij} + r_{ij}\left(x_{ij} - x_{kj}\right) \tag{4}$$

Where X_{kj} is the randomly selected food source, i is randomly chosen parameter index provided k ≠ i and r_{ij} is a random number within the range of (0, 1). After producing the new food source (V_{ij}) its fitness is calculated and a greedy selection is applied between V_{ij} and X_{ij}. This fitness value is the indication of waggle dance of the employed bee. In the third step the employed bees share their food source information with onlooker bees waiting in the hive and then onlooker bees choose a food source depending on the probability values calculated using the fitness values provided by employed bees. The probability value P_i with which X_i is chosen by an onlooker bee can be calculated by

$$P_i = \frac{fitness_i\left(x_i\right)}{\sum_{i=1}^{n} fitness_i\left(x_i\right)} \tag{5}$$

After a food source X_i for an onlooker bee is probabilistically chosen, a neighborhood source V_i is determined by using Eq. (4), and its fitness value is computed. As in the employed bees phase, a greedy selection is applied between V_i and X_i. Hence, more onlookers are recruited to richer sources and positive feedback behavior appears. Employed bees whose solutions cannot be improved through a predetermined number of trials, specified by the user of the ABC algorithm and called "limit" or "abandonment criteria" herein, become scouts and their solutions are abandoned. Then, the converted scouts start to search for new solutions, randomly. For instance, if solution X_m has been abandoned, the new solution is discovered by the scout that was the employed bee of X_i.

4. Experimental Results and Discussion

4.1. Coating Deposition

Mild steel blocks (AISI 1040) of size 20 mm × 20 mm × 8 mm are used as substrates for the deposition of electroless Ni-P-Cu coating. The sample is mechanically cleaned from foreign matters and corrosion products. After that the sample is cleaned using distilled water and a pickling treatment is given to the specimen with dilute (50%) hydrochloric acid for one minute to remove any surface layer formed like rust followed by rinsed in distilled water and methanol cleaning. Table 1 indicates the bath composition and the operating conditions for successful coating of electroless Ni-P-Cu. The cleaned samples are activated in palladium chloride solution at a temperature of 55°C. Activated samples are then submerged into the electroless bath for deposition. The range of coating thickness is found to lie around 20-25 microns. After deposition, the samples are taken out of the bath and cleaned using distilled water.

4.2. Surface Morphology and Composition Study

The characterization of the coating is necessary so that it can be made sure that the coating is properly developed. 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 copper. EDX spectra of the coated surface are shown in Fig. 1. It is found that the coating consists of 11% P, 4% Cu and the remaining is Ni. The scanning electron micrograph (SEM) of Ni-P-Cu coated surface is given in Fig. 2. It is clearly seen that the deposit has coarse nodular structure without any porosity in as-deposited condition. Nodular deposition in a coating depends on nucleation rate and the growth of the deposit. Nucleation rate depends on the bath constituents and the operating condition of the experiment.

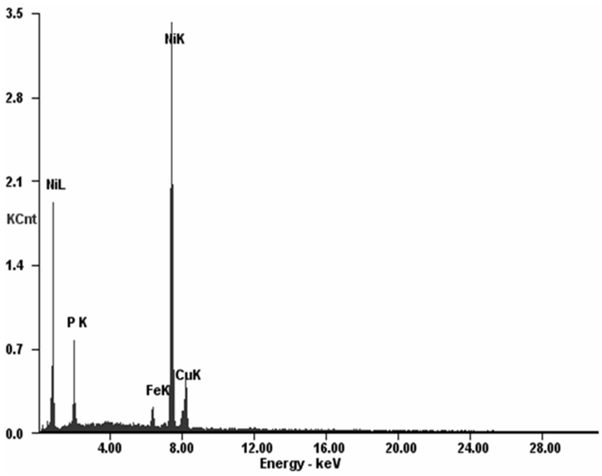

Fig. 1. EDX spectra of Ni-P-Cu coating

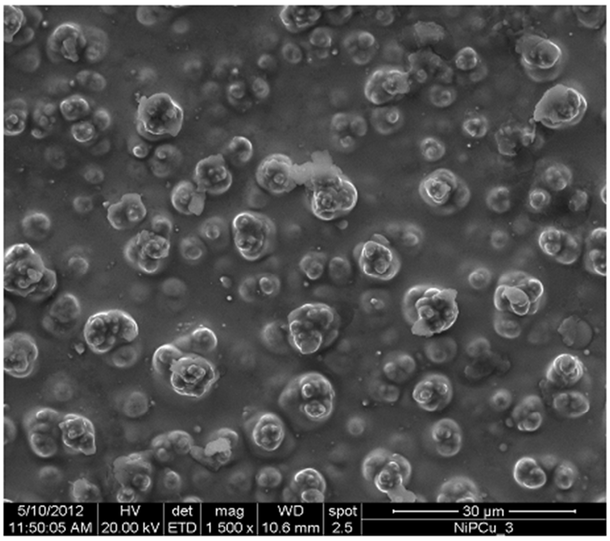

Fig. 2. SEM image of Ni-P-Cu coating

Table 1. Electroless bath constituents

Parameters	Values	Operating condition	Values
Nickel Sulphate (g/l)	25 – 35	pH	9.5
Sodium Hypophosphite (g/l)	10 – 20	Temperature	85°C
Sodium Citrate (g/l)	15	Duration of coating	2 hrs
Copper sulphate (g/l)	0.3 – 0.7	Bath volume (ml)	200

4.3. Profile Measurement and Fractal Calculation

The roughness profile measurement was done using a portable stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The profilometer was set to a cut-off length of 0.8mm, filter 2CR, traverse speed 1mm/s and 4mm traverse length. Roughness measurements on each specimen were repeated four times and an average of four measurements was recorded. The measured profile is digitized and processed through the dedicated advanced surface finish analysis software Talyprofile. Then fractal dimension is evaluated following the procedure outlined in section 2.

5. Optimization Results and Discussion

The electroless Ni-P-Cu coatings involve a number of process parameters which have large impact on the fractal dimension of the coating. Among these, three coating process parameters viz. nickel sulphate, sodium hypophosphite and copper sulphate are selected for this optimization procedure.

Table 2. Main coating parameters with their levels

Design Factors	Unit	Levels		
		1	2	3
Concentration of source of nickel (nickel sulphate solution)	g/l	25	30	35
Concentration of reducing agent (sodium hypophosphite solution)	g/l	10	15	20
Concentration of source of copper (copper sulphate)	g/l	0.3	0.5	0.7

Each controlling parameter has three equally spaced levels. The values of different coating parameters along with their levels are shown in Table 2. In this study a face centre cubic (FCC) response surface methodology (RSM) experimentation plan with 20 experimental run is used to develop the second order polynomial equation. The Minitab software is used to develop the polynomial equation using un-coded values of the coating parameters. The equation is given as below.

$$D = 0.74345 - 0.02101x_1 + 0.05177x_2 + 2.42205x_3 + 0.00027x_1^2 - 0.00173x_2^2 - 1.82955x_3^2 + 0.0025x_1x_3 - 0.0075x_2x_3 \quad (6)$$

Where, x_1 = concentration of nickel source, x_2 = concentration of reducing agent, x_3 = concentration of copper source.

The ABC algorithm is now used to optimize the above-mentioned RSM-based equation. The corresponding computer code for the ABC algorithm is developed in Matlab for easy convergence of the parametric optimization problems. The program was run for 1000 iterations and every time it converges to the optimum solution. It reveals the robustness of the optimization. So the solution can be considered as the best possible solution within the given range. As a higher fractal dimension is the indication of smoother surface, from this analysis the optimum combination of coating process parameters within the given range is obtained. An experiment was performed with those optimum values of coating process parameters obtained from the analysis to confirm the result of the analysis. The result of the confirmation test shows a good agreement with that obtained from the analysis. The confirmation result is shown in Table 3.

Table 3. Result of confirmation test

Main coating parameters	Amount	D obtained from ABC analysis	D obtained from experiment
Nickel sulphate (g/l)	25		
Sodium hypophosphite (g/l)	13.55	1.546	1.540
Copper sulphate (g/l)	0.65		

6. Conclusions

Electroless ternary Ni-P-Cu coating is developed on mild steel substrate by varying three main coating process parameters namely concentration of nickel source (Nickel sulphate), concentration of reducing agent (Sodium hypophosphite) and concentration of copper source (Copper sulphate) and the fractal dimension of the coated surface is evaluated with the help of a Talysurf instrument. The design of experiment was done by FCC response surface methodology with 20 experimental runs. Then artificial bee colony algorithm is successfully employed for finding out the optimal combinations of the three coating process parameters of electroless Ni-P-Cu coatings for better fractal dimension. The optimum value obtained from the analysis shows a good agreement with that of experimental value. The energy dispersive x-ray analysis shows it is a pure ternary coating consisting of nickel phosphorous and copper.

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