

Grey fuzzy logic approach for the optimization of DLC thin film coating process parameters using PACVD technique

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Abstract. Diamond-like carbon (DLC) coatings are widely used in medical, manufacturing and aerospace industries due to their excellent mechanical, biological, optical and tribological properties. The selection of optimal process parameters for efficient characteristics of DLC film is always a challenging issue for the materials science researchers. The optimal combination of the process parameters involved in the deposition of DLC films provide a better result, which subsequently help other researchers to choose the process parameters. In the present work Grey Relation Analysis (GRA) and Fuzzy-logic are being used for the optimization of process parameters in DLC film coating by using plasma assist chemical vapour deposition (PACVD) technique. The bias voltage, bias frequency, deposition pressure, gas composition are considered as input process parameters and hardness (GPa), Young's modulus (GPa), ratio between diamond to graphitic fraction, (I_D/I_G) ratio are considered as response parameters. The input parameters are optimized by grey fuzzy analysis. The contribution of individual input parameter is done by ANOVA. In this analysis found that bias voltage having the least influence and gas composition has highest influence in the PACVD deposited DLC films. The grey fuzzy analysis results indicated that optimum results for bias voltage, bias frequency, deposition pressure, gas composition for the DLC thin films are -50 V, 6 kHz, 4 μ bar and 60:40 % respectively.

1. Introduction

Diamond like carbon (DLC) films have attracted to many researchers due to their excellent mechanical, optical, biological and tribological properties [1]. DLC is an amorphous carbon that contains sp^3 (diamond-like) bonding where sp^2 (graphitic) as the defective carbon fraction, depending on deposition techniques. Due to its excellent properties DLC films have been used in many industrial sectors such as medical, manufacturing and aerospace industries.[1]. For the deposition of DLC thin film various deposition techniques are used and many people have studied the influence of different deposition parameters in a systematic manner [2]. During the deposition of DLC film various input parameters like bias voltage, bias frequency, deposition pressure, gas composition and electrode separation are involved in various techniques. The problem is to determine the optimal response parameters like coating thickness, surface roughness, coating material, hardness, elasticity, residual stress, and fracture toughness of the coating, bond layer, and substrate [3]. Taguchi technique is used to optimize the deposition parameters like bias voltage (V), bias frequency (kHz), deposition pressure (μ bar), gas composition (%) of DLC Coatings with the IC-PECVD technique to get optimum response parameters i.e. hardness and roughness (Ra) [4].

The multi-response optimization problems could be solved by using different methods such as genetic algorithm (GA), artificial neural network (ANN) grey relational analysis (GRA), response



surface methodology (RSM) and fuzzy logic [5]. GRA and fuzzy logic are used as the effective tool for the multi objective optimization. The grey relational grade (GRG) is calculated by doing average of the grey relational coefficient of each response to convert the optimization of the complex performance characteristics into optimization of a single GRG [6]. In the present work GRA and fuzzy logic are being used for the optimization of process parameters in DLC film coating by using PACVD technique.

2. Experimental Description and

Jatti et al. [7] deposited DLC thin film by using plasma enhanced chemical vapor deposition (PECVD) technique. In the experiment the reaction chamber was powered by a 13.56 MHz RF power (50 W) source. For the deposition of the DLC film a p-type silicon wafer (100) of 1.5 cm x 1.5 cm square area of 500 μm thickness was taken as substrate. The total flow rate of methane (CH_4) and hydrogen gases were maintained as 10 sccm by varying the composition of the precursor gases. In the present case bias voltage, bias frequency, deposition pressure and gas composition were considered as input process parameters [Table 1]. An L9 Taguchi orthogonal array was used for the experimental design and it is indicated in table 1.

Table 1. Parameters and their levels [7]

Parameters	Unit	Levels		
		L1	L2	L3
Bias voltage	V	-50	-100	-150
Bias frequency	kHz	0.2	6	40
Deposition pressure	μbar	2	4	6
Gas composition	%	60:40	80:20	90:10

In the present work hardness (GPa), Young's modulus(GPa), I_D/I_G Ratio are considered as response parameters. The mechanical properties like hardness and Young's modulus were found out by nano indentation. From Raman spectra the I_D/I_G ratio was obtained by computing the areas of D-peak and G-peak and taking their ratio.

3. Methodology

3.1 Grey relation analysis(GRA)

Unlike Taguchi the Grey relational analysis (GRA) is used to optimize the multi objective process outcome which make it complicated [8]. The following three steps are used to optimize the process parameter in GRA.

In the first step, the measurement values of centre line average I_D/I_G ratio, hardness (GPa) and Young's modulus (GPa) are to normalize in the range of zero to one which is called grey relational normalization. Such normalization is required since the range and the unit in one response may vary from the others. For the case of hardness and Young's modulus the response characteristics will be 'higher-the-better' and the normalizing equation for them is as follows in equation (1)

$$z_{ij} = (x_{ij} - \text{Min}(x_{ij})) / (\text{Max}(x_{ij}) - \text{Min}(x_{ij})) \quad (1)$$

But in case of I_D/I_G ratio the response characteristics will be 'lower-the-better' and the normalizing equation is stated in equation 2.

$$z_{ij} = (\text{Max}(x_{ij}) - x_{ij}) / (\text{Max}(x_{ij}) - \text{Min}(x_{ij})) \quad (2)$$

Where z_{ij} = Normalized value for i^{th} experiment and for j^{th} response, x_{ij} = Data obtained for the experiments. $\text{Max}(x_{ij})$ and $\text{Min}(x_{ij})$ are the maximum and minimum value of data sequence of a particular experimental outcome.

$$\varphi_{ij} = (\Delta_{\min} - \delta \Delta_{\max}) / (\Delta_{ij} + \delta \Delta_{\max}) \quad (3)$$

Where deviation sequence is denoted by Δ_{ij} , that is the difference between x_{0j} and x_{ij} , x_{0j} is the ideal normalized value or the target value of the j^{th} response, Δ_{\max} is the highest value of Δ , Δ_{\min} is the lowest value of Δ , δ is the distinguishing coefficient usually ranges from 0 to 1, in this case it is taken as 0.5.

$$\gamma_i = \frac{1}{n} \sum_{j=1}^n \varphi_{ij} \quad (4)$$

Where γ_i the grey relational grade and n is the number of process response.

3.2. Fuzzy based modeling

In grey relational analysis, the use of lower-the-better, higher-the-better performance characteristics shows that some kind of uncertainty presents in the results. This problem can be efficiently checked by using fuzzy logic [9].

In fuzzy-logic, the fuzzifier uses different membership function to fuzzify the input grey relational coefficient of the input parameters. Here triangular membership function is taken with five levels for each of the three input value and nine levels for output GFRG. In total nine fuzzy rules are developed from the nine different experiments by correlating the grey relational coefficient with GRG. Mamdani inference engine is used to defuzzify the input values. This inference engine performs fuzzy reasoning on fuzzy rules by taking max-min inference for generating a fuzzy value.

4. Results and Discussion

The experimental results are given in table 2. Here the results obtained by using grey relational analysis, grey fuzzy reasoning grey and ANOVA are presented. From the experimental results the normalized data can be calculated by using equation (1) and (2). The grey relational coefficients and the overall grey relational grade for each of the combination of the parameters is given in Table 3. For the response parameter I_D/I_G ratio 'lower-the-better' criterion is preferred and for hardness and Young's modulus 'higher-the-better' criterion is preferred. In order to obtain a better quality in the performances and to decrease the problem in the data, grey-fuzzy logic method is additionally used for computing the grey fuzzy reasoning grey (GFRG).

Table 2. Input and response parameters [7]

Input parameters					Response parameters		
Expt. No	Bias voltage(V)	Bias Frequency(kHz)	Deposition Pressure(μ bar)	Gas composition (%)	I_D/I_G ratio	Hardness (Gpa)	Young's Modulus (Gpa)
1	-50	0.25	2	60:40	0.11	17.73	186.74
2	-100	6	4	80:20	0.1	16.79	189.94
3	-150	40	6	90:10	0.3	15.63	173.86
4	-50	0.25	2	60:40	0.44	16.57	175.66
5	-100	6	4	80:20	0.32	17.96	191.22
6	-150	40	6	90:10	0.33	16.65	172.81
7	-50	0.25	2	60:40	0.74	16.09	185.46
8	-100	6	4	80:20	0.77	16.88	175
9	-150	40	6	90:10	0.17	17.91	188.59

To generate the grey fuzzy output, MATLAB (2012a) toolbox is used. The grey coefficients of I_D/I_G , hardness and Young's modulus are considered to be the inputs for which triangular membership function having five fuzzy subsets described by lowest, low, medium, high and highest as shown in Fig.1. Similarly for the grey fuzzy reasoning grey (GFRG) nine fuzzy subsets denoted by lowest, very low, low, medium low, medium, medium high, high, very high and highest as shown in Fig.2. Nine fuzzy rules are generated based on the nine experiments for activating the fuzzy inference system using the MATLAB toolbox as shown in Fig.2. In Fig. 3 the location of triangle indicates the determined fuzzy sets for each input and output. The height of the darkened area in each triangle corresponds to the fuzzy membership value for that fuzzy set. The yellow colour shows the input membership function and the blue colour shows the output membership function. It is seen that when the input for I_D/I_G is 0.827, hardness is 0.959 and Young's modulus is 0.778, then the GFRG is 0.848. Similarly, the GFRG values for all the nine experiments are calculated and shown in Table 3. From the Table 3 it is seen that the highest GFRG value of experiment number 5 and 9 are the optimal combination of given parameters.

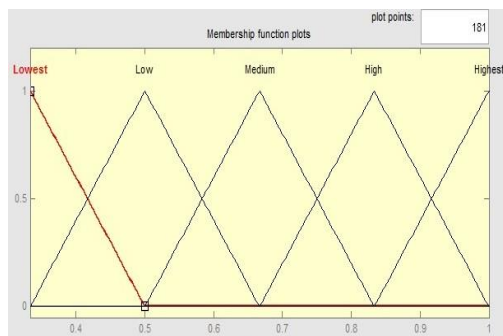


Fig. 1 Membership function for input

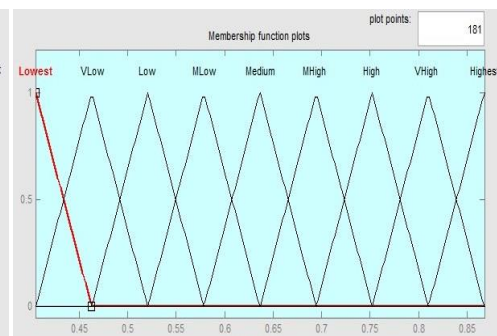


Fig. 2 Membership function for GFRG

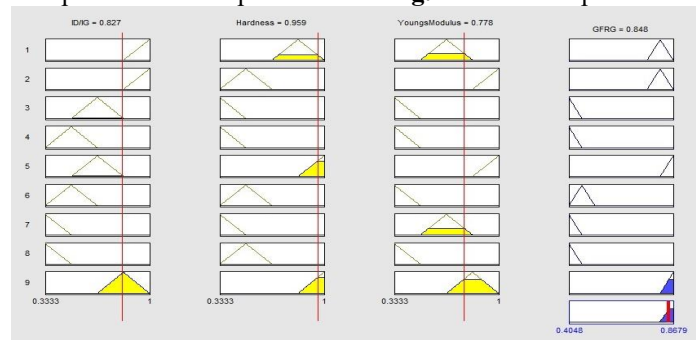


Fig. 3 Fuzzy rule viewer

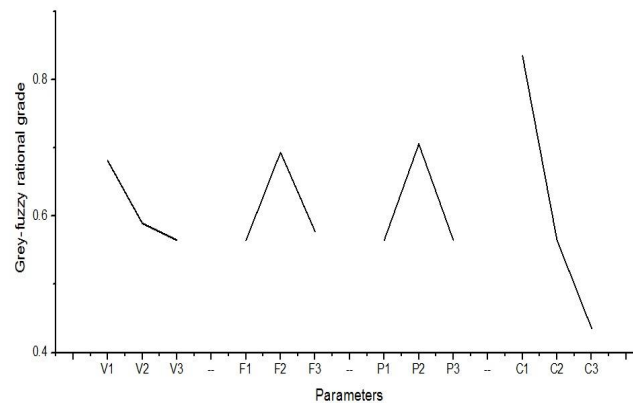
Table 3: Normalized value and Grey relational coefficient

Normalized data				Grey relational coefficient				
Sl no	I_D/I_G ratio	Hardness (Gpa)	Young's Modulus (Gpa)	I_D/I_G ratio	Hardness (Gpa)	Young's Modulus (Gpa)	GRG	GFRG
1	0.9851	0.9013	0.8263	0.81	0.8351	0.6727	0.8263	0.81
2	1	0.4979	0.7923	0.81	0.499	0.878	0.7923	0.81
3	0.7015	0	0.4353	0.424	0.3333	0.3465	0.4353	0.424
4	0.4925	0.4034	0.4413	0.46	0.456	0.3717	0.4413	0.46
5	0.6716	1	0.8679	0.848	1	1	0.8679	0.848
6	0.6567	0.4378	0.4656	0.461	0.4707	0.3333	0.4656	0.461
7	0.0448	0.1974	0.4475	0.424	0.3838	0.6151	0.4475	0.424

8	0	0.5365	0.4048	0.423	0.5189	0.3621	0.4048	0.423
9	0.8955	0.9785	0.8545	0.848	0.9588	0.7777	0.8545	0.848

Table 4: Response table for GFRG

Parameters	Levels		
	L1	L2	L3
Bias voltage(V)	0.6813	0.589	0.565
Bias frequency(kHz)	0.5647	0.693	0.5777
Deposition pressure(μ bar)	0.5647	0.706	0.5653
Gas composition (%)	0.8353	0.565	0.4357

**Fig. 4** GFRG response plot

The average values of grey fuzzy reasoning grade values are tabulated in Table 4. The average values are plotted in the graph which is shown in Fig. 4. From the graph it is found that the optimum results for bias voltage, bias frequency, deposition pressure, and gas composition for the DLC thin films are -50 V (V1), 6 kHz (F2), 4 μ bar (P2) and 60:40 % (C1) respectively.

4.1 ANOVA for GFRG

To find the significance of different input parameters the grey-fuzzy reasoning grade obtained is subjected to ANOVA which is shown in Table 5. As the degrees of freedom for residual error is zero, it does not provide enough data's. When four input parameters with three level values are considered and an L9 Orthogonal Array is chosen for analysis, this kind of things happens. Due to that pooling is performed and is defined as a common practice of revising and re-estimating ANOVA results. For two reasons it is recommended. First one is when a number of factors are included in an experiment, the laws of nature make it probable that half of them would be more influential than the rest and the second one is in statistical predictions, which encounters two types of mistakes: alpha and beta mistakes. When something is important but actually is not, that is called alpha mistake and the beta mistake is just the reverse of the alpha mistake. Unfortunately, the test of significance can be done only when the error term has non zero DoF. Pooling is started with the factor which has the least influence. In this analysis, Bias voltage is having the least influence; hence it is pooled as shown in Table 6.

Table 5: ANOVA table before pooling

Source	DOF	SS	MSS	F value	P value
Bias voltage (V)	2	0.022545	0.011272	**	
Bias frequency (kHz)	2	0.030266	0.015133	**	
Deposition pressure (μ bar)	2	0.039763	0.019881	**	
Gas composition (%)	2	0.249541	0.124770	**	
Error	0	*	*		
Total	8	0.342114			

Table 6: ANOVA table after pooling

Source	DOF	SS	MSS	F value	P value
Bias frequency (kHz)	2	0.03027	0.01513	1.34	0.427
Deposition pressure (μ bar)	2	0.03976	0.01988	1.76	0.362
Gas composition (%)	2	0.24954	0.12477	11.07	0.083
Error	2	0.02254	0.01127		
Total	8	0.03211			

The Grey relational coefficient value is processed through the Fuzzy logic technique and the Grey-Fuzzy relational grade has been calculated. The Fuzzy IF-THEN rule has been utilized for the same and the defuzzification has been done in order to convert the linguistic variable into numerical value. Table 3 shows the Grey-Fuzzy relational grade (GFRG).

5. Conclusion

In this paper, the deposition of DLC film is carried out with the input parameters considered as bias voltage, bias frequency, deposition pressure and gas composition, and the response obtained are hardness, Young's Modulus and I_D/I_G ratio. The input parameters optimized by grey fuzzy analysis. The contribution of individual input parameter is done by ANOVA. In this analysis it is found that bias voltage is having the least influence and gas composition has highest influence. From grey fuzzy analysis it is found that for -50 V bias voltage, 6 kHz bias frequency, 4 μ bar deposition pressure and 60:40 % gas composition, the optimum result will be obtained.

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