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FUZZY LOGIC APPROACH FOR PREDICTING THE EFFECT OF MANUFACTURING PARAMETERS OF Ni-Al_2O_3 COMPOSITE COATINGS BY ELECTRODEPOSITION

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Abstract: The choice of electrodeposition parameters for nickel-alumina composites Ni-Al_2O_3 is very difficult because of the complexity and high cost of the experimental tests, as well as the absence of an exact mathematical model. For this reason, it is essential to use more efficient techniques taking into account all the advantages of formulating the problem under consideration. Among the techniques that prove their effectiveness in solving this type of problem: artificial intelligence techniques, especially the technique of fuzzy logic that never used to solve the electro-deposition parameters problem.
This paper aims to use a fuzzy logic technique to improve the performance of nickel alumina composite coatings, especially micro-hardness which have been manufactured using a conventional electro-deposition process.
The fuzzy logic technique, used for predicting the values of processing parameters: temperature of bath, current density, pH of electrolyte, agitation speed, and concentration of ceramic particles Al_2O_3 in bath. The fuzzy model developed for the determination of microhardness is formed (fuzzy rules) and tested using experimental data. The objective was to determine the influence of manufacturing parameters on the micro-hardness of composite: Ni-Al_2O_3.
The results indicated that the current density and bath temperature are the main parameters that determine the micro-hardness of the deposit. The fuzzy model for predicting micro-hardness of composite: Ni-Al_2O_3 was tested by using the experimental data. The average error of the test data was 3.88%, which corresponds to an accuracy of 96.12%.
Key words: Electro-deposition, Ni-Al_2O_3 composite coatings, Fuzzy logic, Micro-hardness.

1. INTRODUCTION

The manufacture of coatings by electrodeposition has been known for a long time and is the subject of several studies. [19]
The advantages of composite coatings are illustrated in several studies [9, 10, 16-19]. The presence of the ceramic particles provides a great improvement on the mechanical properties of the coating. In the literature [2, 10, 13, 19] we found that the researchers used several types of ceramic particles namely: Al_2O_3, SiC, TiO_2, and TiC.
The Ni-Al_2O_3 coating is one of the most studied coatings, where the Al_2O_3 ceramic particles are incorporated into the nickel metal matrix.
A good quality of Ni-Al_2O_3 composite coating should contain an optimal amount of Al_2O_3 particles, and the particles should be uniformly disposed in the matrix, which necessitates an optimal choice of manufacturing parameters.
Conventional techniques [4, 6, 9, 10, 17, 18 and 20] were used to determine the effect of the manufacturing parameters of the Ni-Al_2O_3 composite on the characteristics of this coating.
Conventional techniques [4, 6, 9, 10, 17, 18, and 20] were used to determine the effect of the manufacturing parameters of the Ni-Al_2O_3 composite on the characteristics of the coating. These techniques are based on the electrocodeposition method (CECD), where the electrodes are placed vertically or horizontally in the bath so that the particles in the bath are held in suspension by continuous stirring.
Thus, soft computing techniques [2, 5, 7, 8, 11, 14 and 15] have been developed to solve the problem of the choice of production parameters for Ni-Al_2O_3 composite coatings because of their ability to be predicted and modeled different phenomena.
These techniques are used when exact mathematical models are not available; these techniques represent the best method of analyzing the experimental results. The progress on the use of these approaches for determining the effects of composite coatings manufacturing parameters is late compared to other progress in the industry.
Its use has been limited to the method of design of experiment (DOE) [14]. However, this technique has some disadvantages, namely: uncertainty, inaccuracy and approximation.
It is proposed to use the fuzzy logic approach to study

the effect of $Ni-Al_2O_3$ coating papers on the micro-hardness of the coating.
Compared to other methods, the use of fuzzy logic is simpler and does not require a lot of hardware and software [1, 22]. For the manufacturing process of the $Ni-Al_2O_3$ composite coatings, the results can be obtained by carrying out only a few experiments. On all soft-computing approaches, fuzzy logic is appropriate for predicting parameters such as micro-hardness using a limited number of tests.
This paper focuses on the application of the fuzzy logic technique to study the influence of electrodeposition parameters on the micro-hardness of $Ni-Al_2O_3$ composite coatings.

2. FUZZY LOGIC

2.1 Definition

Fuzzy logic is an extension of Boolean logic created by Lotfi Zadeh in 1965, [3], based on his mathematical theory of fuzzy sets, which is a generalization of classical set theory. By introducing the concept of degree in the verification of a condition, thus allowing a condition to be in another state than true or false, fuzzy logic confers a very appreciable flexibility on the reasoning that uses it, the taking into account of inaccuracies and uncertainties, [12].

2.2 Principle

The principle of fuzzy logic control approaches the human approach in the sense that the variables processed are not logical variables (in the sense of binary logic, for example) but linguistic variables, close to everyday human language. Moreover, these linguistic variables are treated by rules which refer to certain knowledge of the system behaviour, [12].

3. PROBLEMATIC

In this paper a fuzzy model was developed to study the effect of electrodeposition parameters (temperature of bath, current density, pH of electrolyte, agitation speed, concentration of ceramic particles Al_2O_3 in bath) on the micro-hardness of the coating.

4. PROCEDURE AND EXPERIMENTAL DATA

Our study is based on the experimental work developed by S. Jeyaraj et al., [14] that used a Watts bath for the preparation of composite coatings $Ni-Al_2O_3$.
To study the effect of the electrodeposition parameters on the hardness of the coating we propose to use a simulation method based on the technique of fuzzy logic implanted under MATLAB, based on the experimental data grouped in Table 1 obtained since the study of S. Jeyaraj et al., [14].

Table 1. Experimental data, [14]

Essai	I (A/dm^2)	pH	T (°C)	Co (g/l)	Va (rpm)	H (HV)
1	1	2.5	30	10	200	267
2	1	2.5	30	10	250	227
3	1	2.5	30	10	300	243
4	1	3.5	45	20	200	547
5	1	3.5	45	20	250	451
6	1	3.5	45	20	300	418
7	1	4.5	60	30	200	389
8	1	4.5	60	30	250	374
9	1	4.5	60	30	300	496
10	2	2.5	45	30	200	294
11	2	2.5	45	30	250	482
12	2	2.5	45	30	300	495
13	2	3.5	60	10	200	362
14	2	3.5	60	10	250	411
15	2	3.5	60	10	300	329
16	2	4.5	30	20	200	513
17	2	4.5	30	20	250	493
18	2	4.5	30	20	300	307
19	4	2.5	60	20	200	622
20	4	2.5	60	20	250	563
21	4	2.5	60	20	300	571
22	4	3.5	30	30	200	614
23	4	3.5	30	30	250	387
24	4	3.5	30	30	300	465
25	4	4.5	45	10	200	655
26	4	4.5	45	10	250	639
27	4	4.5	45	10	300	579

For the table 1 the elements are: I-current intensity, T-temperature bath, pH of electrolyte, Co- concentration of ceramic particles Al_2O_3, Va-agitation speed, H-micro-hardness of the coating.

5. FUZZY SYSTEM

A fuzzy system with five inputs: current density (I), temperature of bath (T), pH of electrolyte, concentration of ceramic particles Al_2O_3 in bath (Co), and agitation speed (Va), and one output: micro-hardness of the coating, was used in our study (H).

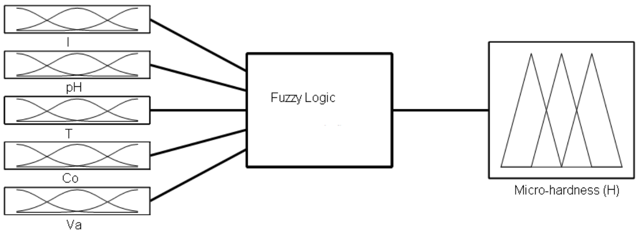


Fig. 1. Fuzzy system

6. FUZZY MODELING

6.1 Fuzzy variables

In the construction of our fuzzy model the inputs and outputs of the fuzzy system are chosen as illustrated in figure 1.
The minimum and maximum values of the input and output variables are grouped in Table 2.

Table 2. Minimum and maximum values of the input and output variables for the fuzzy system

Input parameters		
	Min value	**Max value**
Current density I (A/dm^2)	1	4
Temperature of bath T (°C)	30	60
pH	2.5	3.5
Concentration of ceramic particles Al_2O_3 Co (g/l)	10	30
Agitation speed Va (rpm)	200	300
Output parameters		
Micro-hardnessH (HV)	227	655

All the variables used in our study are divided into categories called linguistic variables. Each linguistic variable corresponds to a numerical data interval.
The linguistic variables for the first variable (current density) are chosen as indicated in the figure 2.

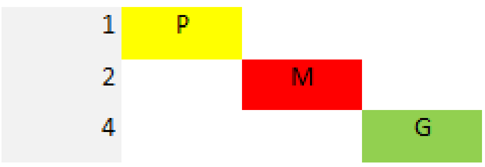


Fig. 2. Linguistic variables for current density (A/dm^2)

The linguistic variables for the second variable (temperature of bath) are chosen as shown in figure 3.
The linguistic variables for the third variable (pH of electrolyte) are chosen as shown in figure 4.
The linguistic variables for the fourth variable (concentration of ceramic particles Al_2O_3 in bath) are chosen as shown in figure 5.

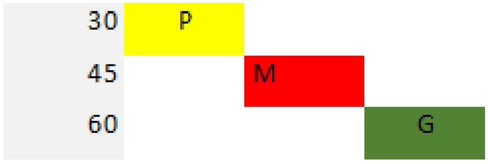


Fig. 3. Linguistic Variables for temperature of bath

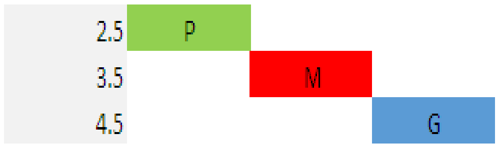


Fig. 4. Linguistic variables for pH of electrolyte

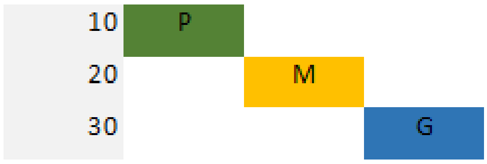


Fig. 5. Linguistic variables for concentration of ceramic particles Al_2O_3 in bath (g/l)

The linguistic variables for the fifth variable (agitation speed) are chosen as indicated in the figure 6.

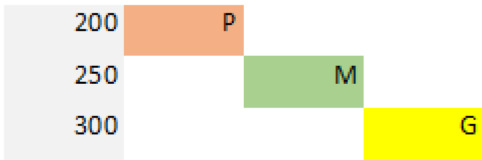


Fig. 6. Linguistic variables for agitation speed (rpm)

In order to define the linguistic variables for the outputs we used the scatterplot (Figure 7) wich shows the distribution of micro-hardness values in the univers of discours, which we help to determine the fuzzy intervals following to the values concertation of the output in each interval.
Based on the previous figure, the linguistic variables for output (micro-hardness) are chosen as shown in figure 8.

6.2 Membership functions

A fuzzy set is defined to its membership function, which corresponds to the characteristic function notation.
The membership functions take different forms, including triangular, trapezoidal, Gaussian and sigmoid. In the present study, the Gaussian membership functions were used for the input and the output parameters.
The membership functions used are represented in the figure 9.

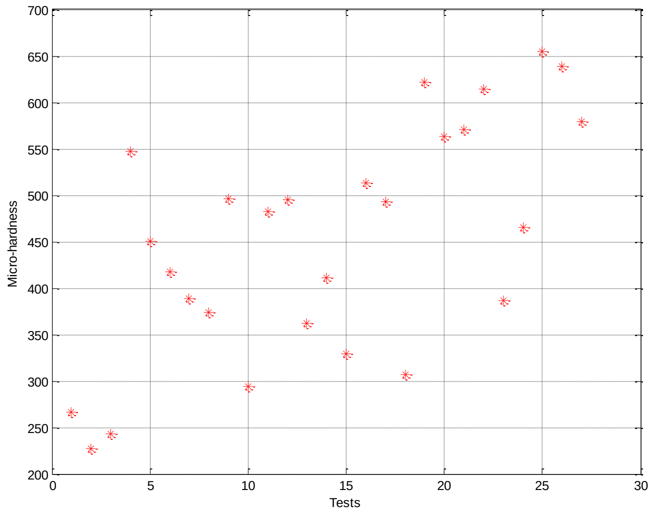


Fig. 7. Scatterplot of micro-hardness (HV)

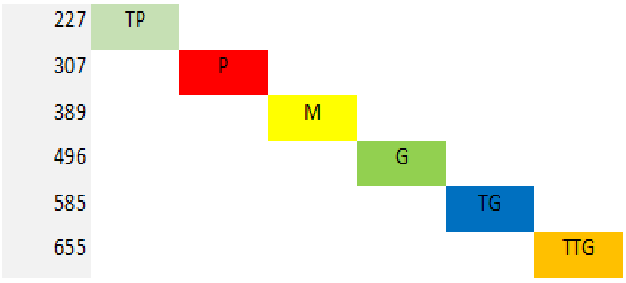
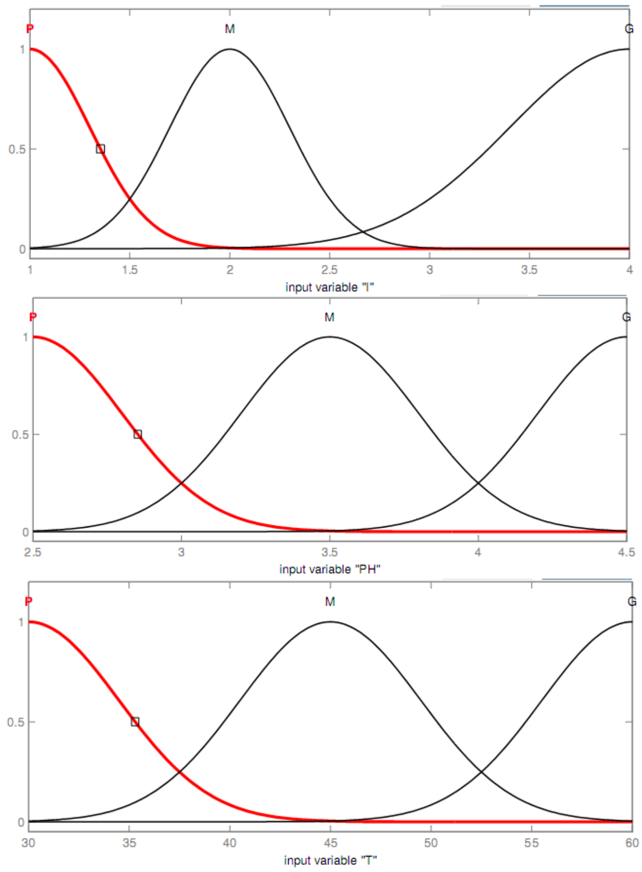


Fig. 8. Linguistic variables for micro-hardness (HV)



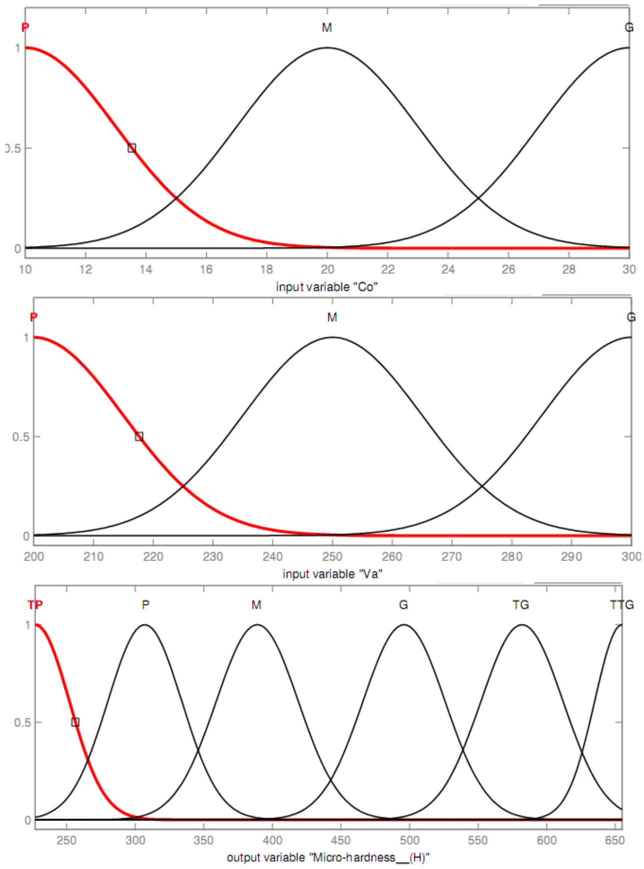


Fig. 9. Membership functions

6.3 Fuzzy rules

Twenty-seven (27) fuzzy rules were established based on the experimental conditions indicated in the table 3. By adhering to the maximum-minimum composition process, the fuzzy logic of these rules produced a fuzzy output.

Each rule takes the following form:

If I is (linguistic variable) and T is (linguistic variable) and pH is (linguistic variable) and Co is (linguistic variable) and Va is (linguistic variable) then H is (linguistic variable).

The fuzzy rules elaborated are grouped in the table 3.

Table 3. Table of inferences

Test	I	pH	T	Va	Co	H
1	P	p	P	P	P	TP
2	P	p	P	P	M	TP
3	P	p	P	P	G	TP
4	P	M	M	M	P	TG
5	P	M	M	M	M	G
6	P	M	M	M	G	M
7	P	G	G	G	P	M
8	P	G	G	G	M	M
9	P	G	G	G	G	G

10	M	P	M	G	P	P
11	M	P	M	G	M	G
12	M	P	M	G	G	G
13	M	M	G	P	P	M
14	M	M	G	P	M	M
15	M	M	G	P	G	P
16	M	G	P	M	P	G
17	M	G	P	M	M	G
18	M	G	P	M	G	P
19	G	P	G	M	P	TG
20	G	P	G	M	M	TG
21	G	P	G	M	G	TG
22	G	M	P	G	P	TG
23	G	M	P	G	M	M
24	G	M	P	G	G	G
25	G	G	M	P	P	TTG
26	G	G	M	P	M	TTG
27	G	G	M	P	G	TG

7. RESULTS AND DISCUSSION

The results are obtained during defuzzification which is the last step in fuzzy logic. This step consists in transforming the linguistic value from a fuzzy controller into a numerical value.

7.1 Study of the accuracy and error of the fuzzy system

The errors were calculated by measuring the difference between the measured value and the predicted value. Errors can be calculated using equation (1). The percentage of individual errors was obtained by dividing the absolute difference of the prediction by the measurement value.

$$e_i = \left(\frac{|D_{ex} - D_P|}{D_{ex}} \right) \times 100\% \qquad (1)$$

Accuracy is calculated by finding the approach of the predicted value to the measured value. In quation (2), A is the precision of the model and N is the total number of data sets tested. The precision of the model is the average individual accuracy.

$$A = \frac{1}{N} \sum \left(1 - \frac{|D_{ex} - D_P|}{D_{ex}} \right) \times 100\% \qquad (2)$$

Table 4 shows all the results obtained by our fuzzy system.

Table 4. Results of the fuzzy system

Tests	Electrodeposition parameters					Micro-hardness results			
	I [A/dm^2]	pH	T [°C]	Co [g/l]	Va [rev/min]	H_{ex} Experimental Hardness, [HV]	H_p Predicted Hardness, [HV]	e Error [%]	A Accuracy [%]
1	1	2.5	30	10	200	267	254	4.87	95.13
2	1	2.5	30	10	250	227	255	12.33	87.67
3	1	2.5	30	10	300	243	253	4.12	95.88
4	1	3.5	45	20	200	547	579	5.85	94.15
5	1	3.5	45	20	250	451	495	9.76	90.24
6	1	3.5	45	20	300	418	389	6.94	93.06
7	1	4.5	60	30	200	389	391	0.51	99.49
8	1	4.5	60	30	250	374	391	4.55	95.45
9	1	4.5	60	30	300	496	495	0.20	99.80
10	2	2.5	45	30	200	294	310	5.44	94.56
11	2	2.5	45	30	250	482	495	2.70	97.30
12	2	2.5	45	30	300	495	495	0.00	100.00
13	2	3.5	60	10	200	362	391	8.01	91.99
14	2	3.5	60	10	250	411	390	5.11	94.89

15	2	3.5	60	10	300	329	310	5.78	94.22
16	2	4.5	30	20	200	513	495	3.51	96.49
17	2	4.5	30	20	250	493	495	0.41	99.59
18	2	4.5	30	20	300	307	310	0.98	99.02
19	4	2.5	60	20	200	622	639	2.73	97.27
20	4	2.5	60	20	250	563	581	3.20	96.80
21	4	2.5	60	20	300	571	581	1.75	98.25
22	4	3.5	30	30	200	614	579	5.70	94.30
23	4	3.5	30	30	250	387	391	1.03	98.97
24	4	3.5	30	30	300	465	495	6.45	93.55
25	4	4.5	45	10	200	655	639	2.44	97.56
26	4	4.5	45	10	250	639	639	0.00	100.00
27	4	4.5	45	10	300	579	581	0.35	99.65
									96.12%

The functions obtained by fuzzy logic are shown in figures 10 to 13.

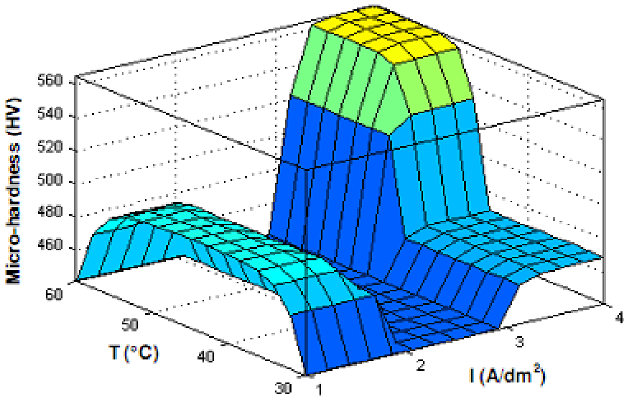


Fig. 10. Function *H=f (T, I)* with *pH = 3.5*, *Co=20 g/l* and *Va =300 rpm*

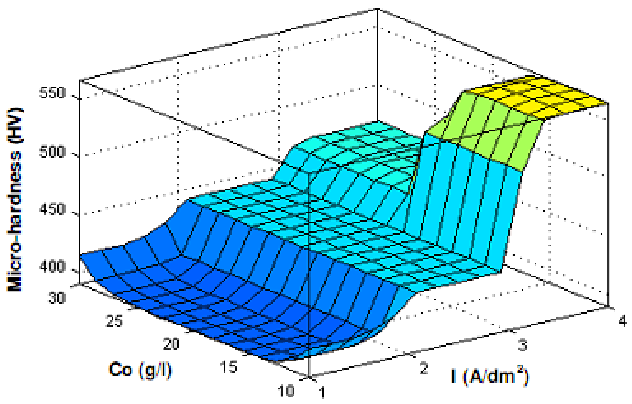


Fig. 11. Function *H=f (Co, I)* with *T=45°*, *pH= 3.5*, and *V Va =300 rpm*

The figure 10 shows the variation of the micro-hardness as a function of the temperature and the current density. It is clear that the maximum values of the micro-hardness are obtained for maximum values of the temperature and the current density.

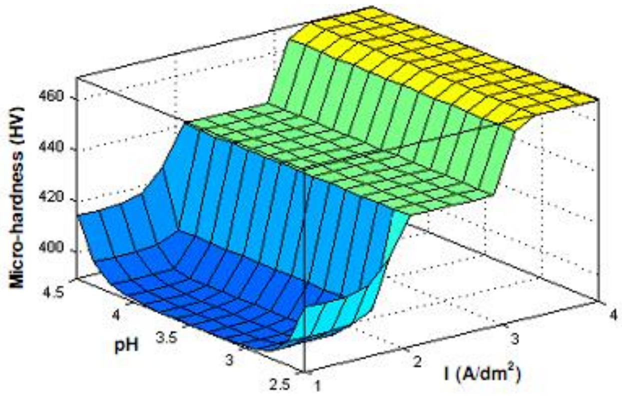


Fig. 12. Function *H=f (pH, I)* with *T=45°*, *pH = 3.5*, and *Vf =300 rpm*

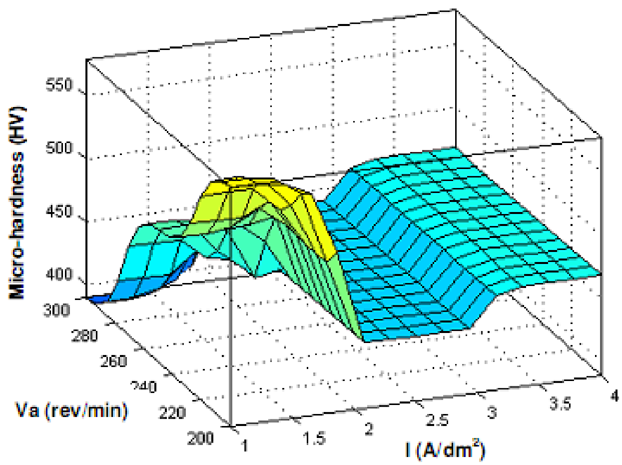


Fig. 13. Function *H=f (pH, I)* with *Co=20g/l*, *T=45°*, and *Vf =300 rpm*

Therefore, in order to have a hard coating, the highest values (as far as possible) of the temperature and the current density must be used.
The figure 11 shows that there is a positive correlation between hardness and current with an Al_2O_3 concentration of 10 to 15. It also note that in each case the concentration of Al_2O_3 increases, the hardness is clearly decreased.
The figure 12 shows the variation of the hardness as a function of the pH and the current density. It is clear that the the maximum values of the hardness are obtained for maximum values of the pH and the current density.
The variation of the hardness as a function of the current density and the agitation speed is shown in figure 13, where it is noted that the value of the micro-hardness is maximum when the current is about 1.5 A/dm^2.
It is clear that the decrease in agitation speed and current density at the same time indicates a remarkable increase in the micro-hardness of the deposit.
From the above figures, we note that the current density and the temperature of the bath constitute the both main parameters, which have the greatest influence on the micro-hardness. The maximum micro-hardness is reached for temperatures of 45 ° C and current density of 4 A/dm^2.

7.2 Validation of results

The relationships between the simulation values and the experimental values are shown in figure 14.

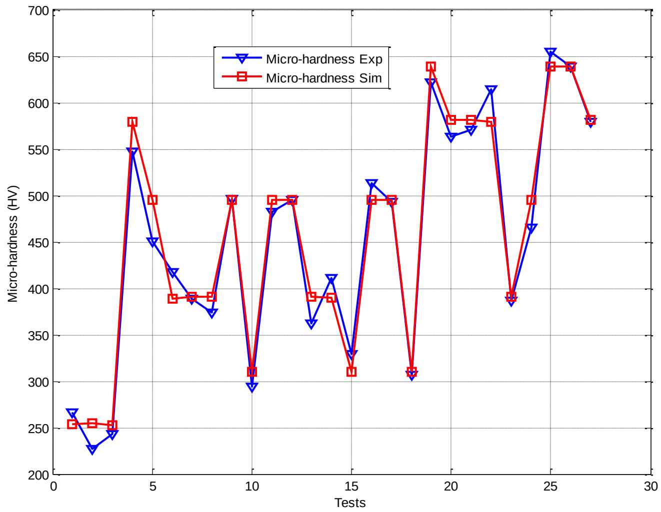


Fig. 14. Comparison of fuzzy logic model prediction with the measured results of micro-hardness

This figure indicates a very close correlation between the experimental values and the fuzzy predicted values.
In order to validate our results the error and the precision of the fuzzy model was calculated.
The mean percentage error for the prediction of the fuzzy model was 3.88%. The error level indicates that the results of the micro-hardness predicted by the fuzzy logic model were close to the actual experimental values.
Table 4 shows that the precision of the fuzzy model was 96.12%. The precision shows that the proposed model can be used successfully to predict the micro-hardness of Ni-Al_2O_3 composite coatings.

8. CONCLUSIONS

The objective of our study was to predict the influence of processing parameters - current density (I), temperature of bath (T), pH of electrolyte, concentration of ceramic particles Al_2O_3 in bath (Co), and agitation speed (Va) on the micro-hardness composite coatings: Ni-Al_2O_3.
The study we conducted led us to conclude that:
-Current density and bath temperature are the main parameters that determine the quality of the deposit. They are indissociable from one another because they are opposite effects.
-The effect of the other parameters (pH, agitation speed, of ceramic particles Al_2O_3 in bath) is not negligible.
-The fuzzy model used for the prediction of Ni-Al_2O_3 composite parameters showed good agreement between the simulation results and the experimental results.
The results obtained using the fuzzy model, were proved by a comparative study with experimental results.
The predicted values are consistent with the actual micro-hardness, with an average error percentage of 0.27% and are well associated with the experimental values.
In perspective other methods of soft computing eg neural networks [23] can be used to to predict microhardness of the composite coating Ni-Al_2O_3.

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