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Comparing the Ranking of Cobalt Coating Microstructures, Produced by Direct Current through Experimental Studies and the Analytic Hierarchy Process

H. Shirdastian[1,2,*], N. Towhidi[1], S.R. Allahkaram[1], M. Siadat Cheraghi[1]

[1] *School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran*
[2] *MBA Department, Faculty of Social Sciences, University of Imam Khomeini, Qazvin, Iran*

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In recent years, cobalt has been known as an alternative coating material to chromium in corrosion and erosion resistant applications. Extensive research has been carried out on a variety of electroplated cobalt coatings. In this study, for the first time, the relative priority of cobalt coatings has been evaluated by using the Analytic Hierarchy Process (AHP), in combination with empirical methods. In the first step, Cu substrates have been coated with Co under different experimental conditions. The SEM micrographs of Co coatings have been analyzed via image analysis (Clemex) software. In the second step, through the AHP and the Expert Choice software, benefiting from expert opinions, the relative weights of the effective parameters with an influence on microstructure have been calculated. Subsequently, by using the weights obtained, the relative priority of alternatives was calculated and the quality of coatings was ranked. The predicted ranking has been found to be in consistence with the experimental results. This result shows that before experimental tests, the best alternatives to achieve the ultimate goal could be anticipated. This anticipation leads to reduce in trial and error and the multiplicity of the tests in investigations.

Keywords: Co-electroplating, Coating microstructure, Analytic Hierarchy Process (AHP), Expert choice and clemex software

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1. INTRODUCTION

Increasing demand for transformers, motors and generators, in order to manufacture electrical equipment and devices that are used at high temperatures, caused extensive research on the magnetic susceptibility and high iron group alloys having high Curie temperature. Cobalt and its alloys have suitable magnetic and electrical properties for applications in technologies such as magnetic recording, core material of transformers, thin layer induction and magnetic - impedance sensors [1]. Recent researches have shown that the Nano crystalline cobalt coatings can be replaced by chromium layers as a material for erosion resistant coatings [2]. Cobalt coatings via electroplating have a range of applications due to their attractive appearance, hardness and resistance against oxidation. Moreover, electroplating offers a better control over thickness and properties of the coating material as compared to other coating methods [3].

According to favorable physical, chemical and metallurgical properties of microstructures, the need to develop methods that present easier and faster ways to achieve is strongly felt. In this study, while "The Analytic Hierarchy Process (AHP)" is introduced as a powerful method for multi-criteria decision making in various ways, the possibility of utilizing this method in engineering science and especially in Metallurgy and Material Engineering for further targeting research is presented.

In this paper, the quality of cobalt coatings on Cu substrates, deposited by direct current electroplating, has been assessed under five different experimental conditions, and then ranked by the AHP. Finally, application of the AHP in the selection of optimal electroplating parameters & alternatives is discussed.

2. MATERIAL AND METHODS

In this study, the relative priority of the cobalt coatings applied by direct current in different conditions is ranked by experimental and theoretical studies. The experimental procedure is studied on the results of laboratory and theoretical findings through the AHP and Expert Choice software based on the AHP algorithm.

2.1 Experimental Study

The purpose of this research is to evaluate the grain size data for five cobalt coatings on copper. So, after applying the Cobalt on the surface, the SEM microstructures of coatings are analyzed via the Clemex Vision Professional Edition. For a more detailed visual analysis of pictures, the filters of Adobe Photoshop software are used. By using the Clemex software, the total number, mean size, length, width and diameter of grains are worked out. Then the coatings are ranked based on the grain length.

2.2 Theoretical study through the AHP

The goal in this review is to achieve the smallest grain size. The pairwise comparison matrixes between effective factors and alternatives were prepared and completed by the experts. Then by using the AHP algorithm, the ranking of the effective criteria and five coating alternatives was obtained.

* solahai@gmail.com
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2.2.1. The Analytic Hierarchy Process (AHP)

The "Analytic Hierarchy Process" was developed by Thomas L. Saaty for the first time in 1970 [4]. The main components of this method are [5]:

1. Determining the main goal and configuring the decision components: in this process, choosing the smallest grain length, which is depended on various factors, is divided to simpler sub factors.
2. Constructing a set of pairwise comparison matrixes in which criteria in each level of hierarchy diagram compare with respect to upper level and also alternatives compare to each other with respect to criteria.
3. Evaluating the relative priority: By mathematical calculations on pairwise comparison matrixes and comparing the obtained relatives, the best alternative for coating selects.

2.2.2. Pairwise comparison matrix

In pairwise comparison matrix, affective criteria in decision-making in each level, i.e. current density, temperature, pH and saccharin or five in study coating alternatives are compared to each other. In this matrix, main diameter is always one and the symmetric data is reversed [6]. The advantage of this pairwise comparison is that at the moment of paired comparisons, only two criteria or alternatives are compared with each other.

For implementation the pairwise comparison matrixes in qualitative data, a numerical basis is required to show the importance and priority of one alternative to other with respect to the criteria and one criterion to other with respect to the purpose. Thomas Saaty has proposed scale of Table 1 [7].

2.2.3. Algorithm of AHP

To achieve criteria weights and alternatives rankings, the following algorithm is performed on the $n \times n$ pairwise comparison matrixes. Thomas Saaty proved that the best way to turn pairwise comparison matrixes to weights and alternatives ranking is calculating the “Eigenvector». To calculate the Eigenvector and final weights, the following steps had been proposed [5]:

The $n \times n$ pairwise comparison matrix squares and a new matrix is derived.

Elements located in each row of the new matrix add together. The result is a $n \times 1$ matrix.

Elements located in the $n \times 1$ matrix add together and a number is the result.

1. Elements of $n \times 1$matrix are divided by the result of step 3 and the "Eigenvector" achieves.

To calculate the final weights, the following steps should be done on the eigenvector:

For the obtained matrix of step 1, steps 1 to 4 are repeated to achieve a new eigenvector.

2. The difference between the previous eigenvector and the eigenvector of step 5 is calculated.

The algorithm stops when the difference of two eigenvector of two consecutive rounds, is less than a certain amount.

By algorithm stopping, final weights of criteria or alternatives prepared [8]. For determining the best alternative, weight matrix of alternatives compared to each criterion must be multiplied by matrix of final criteria weight. The largest number is the best alternative for choosing [9].

2.3 Comparison of Experimental and AHP Results

In order to implement the feasibility of Analytic Hierarchy Process rather than laboratory trial and error, results of experimental and theoretical studies were compared to each other eventually.

3. RESULTS AND DISCUSSION

3.1 Experimental Study

Experimental conditions of five coated Cu samples are presented in Table 2 and the corresponding SEM micrographs are shown in Fig. 1.

By analyzing of SEM pictures via the Clemex software, grain number, size, length, width and diameter of five coatings were extracted. The data are presented in Table 3.

In the last column of this table, the coating’s rank is listed based on the size of the grains. Based on Table 3, the coating named «Current Density = 5 mA/cm²» by 208 nm in length had the smallest grain size and the coating named «Temperature = 25 °C» by 2704 nm in

Table 1 – A numerical scale for determining the importance of criteria and alternatives in pairwise comparison matrixes [7]

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong	An activity is favored very strongly over another
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Table 2 – Experimental conditions of five applied coatings on copper samples

	Coating Name	Current Density (mA/ cm²)	pH	Saccharin (g/l)	Temperature (°C)	Time (Min)
A	pH = 1.5	20	1.5	0.25	45	30
B	Current Density = 5 mA/cm²	5	3	0.25	45	30
C	Current Density = 40 mA/cm²	40	3	0.25	45	30
D	Temperature = 70 °C	20	3	–	70	30
E	Temperature = 25 °C	20	3	–	25	30

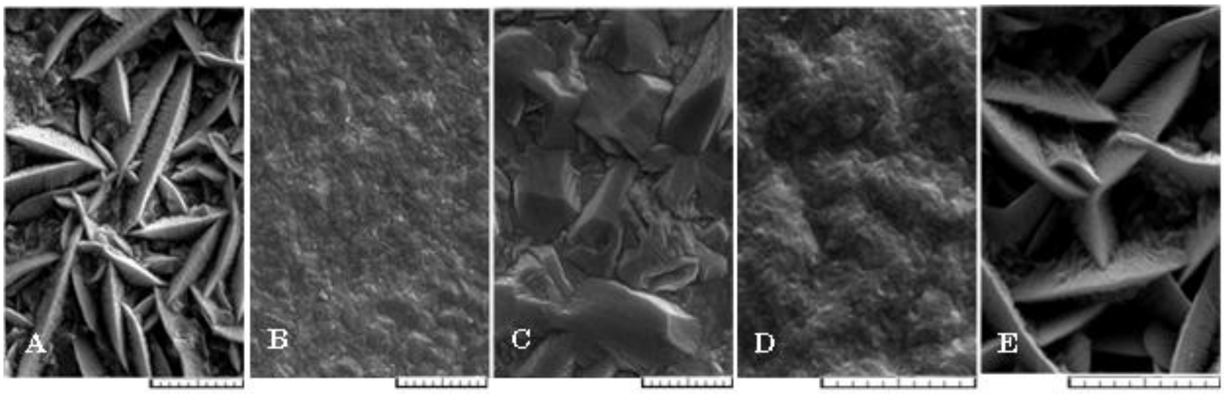

Fig. 1 – SEM micrographs of the cobalt coatings in 2μ scale, as indicated in Table 2

Table 3 – Experimental conditions of the five Co coatings on Cu samples

	Coating Name	Count	Length (nm)	Width (nm)	Diameter (nm)	Rank based on length
A	pH = 1.5	98	2588	788	417	4
B	Current Density = 5 mA/cm²	486	208	171	178	1
C	Current Density = 40 mA/cm²	171	1443	1224	921	3
D	Temperature = 70 °C	94	442	178	114	2
E	Temperature = 25 °C	14	2704	768	1076	5

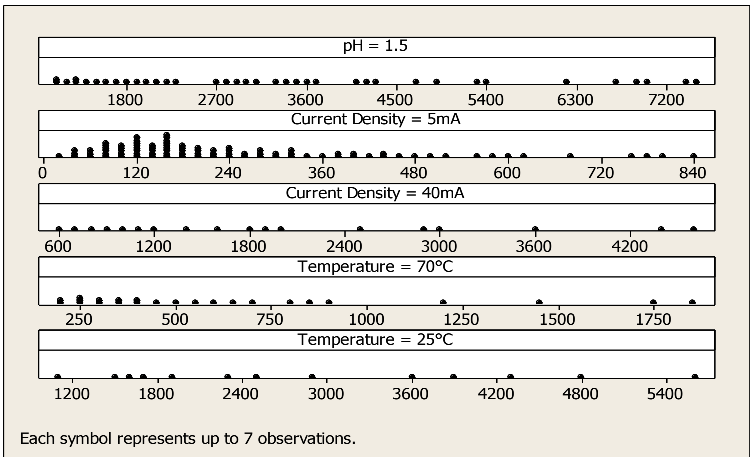

Fig. 2 – The dotplot grain size of the Co coatings, presenting the distribution of lengths in nm. Each symbol represents up to 7 grains

length had the largest grain size. For observing how the grain size distribution was, using a dotplot diagram, the length diagram of Co coatings has been drawn. The graph is presented in the Fig. 2. In this graph, each symbol represents up to 7 grains.

3.2 Theoretical Study

In this study, the aim was to achieve the smallest grain (first row). This goal increases the corrosion resistance and improves metallurgical properties of the surface. The hierarchy diagram of achieving the smallest grain length in a cobalt coating is shown in

In the second row of hierarchical diagram, four factors of pH, current density, temperature and the amount of saccharin have been introduced as effective characteristics on the microstructure. Given that the different range of these factors have different effects on grain size, in the third row each criterion is divided into several subs with an effect on the grain size. In this

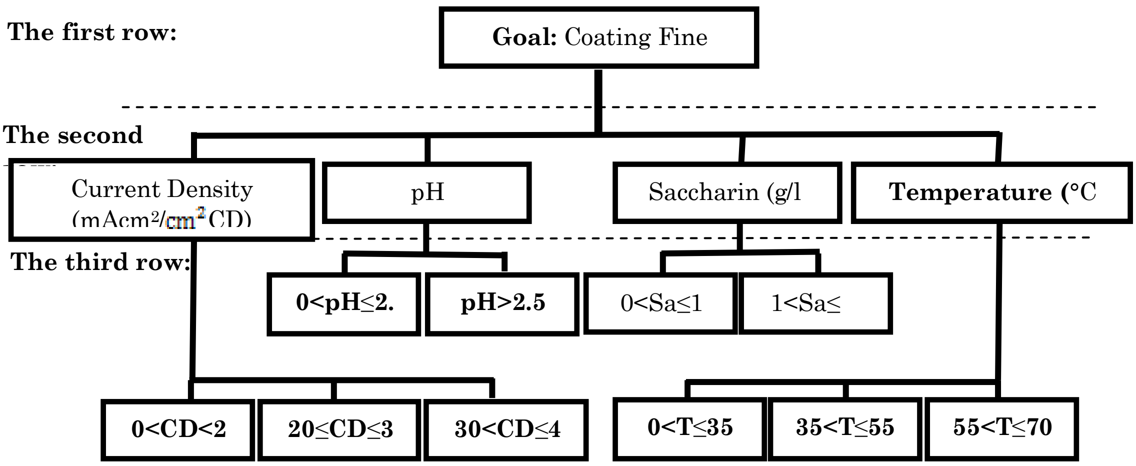

Fig. 3 – Hierarchy diagram of criteria for achieving a fine-grained cobalt coating

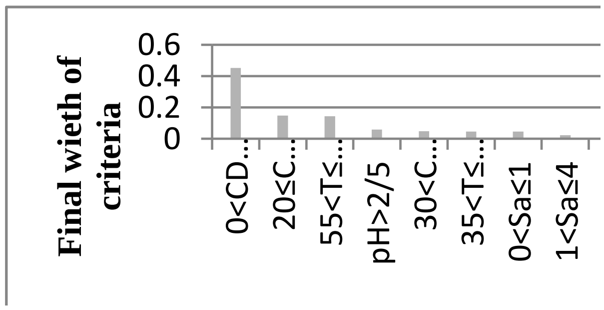

Fig. 4 – Diagram of final weights of effective criteria

Table 4 – The comparison matrix of the second row of hierarchical diagram presented in Fig. 3

	CD	T	pH	Sa
Current Density	1	5	7	7
Temperature	1/5	1	3	4
pH	1/7	1/3	1	1
Saccharine	1/7	1/4	1	1

row, the current density for short is shown: (CD), Saccharin: (Sa) and temperature: (T). Then pairwise comparison matrixes of criteria developed and completed by the experts. In Table 4, pairwise comparison matrix of the second row of Fig. 3 is presented and in Fig. 4 final weight results of effective criteria are shown.

Five possible coatings, using AHP for selecting the best, is shown in Table 5. These coatings were ranked according to the weights of criteria by AHP algorithm through Expert Choice software. The results of these coating priorities and rank of them are presented in the last column of Table 5.

3.3 Comparison of experimental and theoretical results

By comparing the grain size of the coatings described in Table 5, and their rank in the AHP, Table 6 was obtained. According to this Table, it is noted that the results of experimental studies and AHP acknowledge each other.

Table 6 – Comparing the results of experimental length and given length rank from AHP

Coating Name	Experimental length (nm)	Given length rank from AHP
Current Density = 5 mA/ cm²	208	1
Temperature = 70 °C	442	2
Current Density = 40 mA/ cm²	1443	3
pH = 1.5	2588	4
Temperature = 25 °C	2704	5

4. CONCLUSION

1. Amongst five examined coatings, the coating obtained using 5 mA/cm² current density, pH 3, electrolyte saccharin of 0.25 grams per liter and a temperature of 45 °C during 30 min, had the most favorable microstructure, namely, the smallest grain size of about 200 nm.
2. Since the experimental data of grain structure in various conditions and results of Analytic Hierarchy Process (AHP) pattern are consistent, utilizing AHP in experimental fields of metallurgy and material engineering science and other technical sciences is possible.

Table 5 – Experimental conditions, relative priorities and ranking of coatings for choosing the best coating with the smallest grain size

Coating's alternatives	Current Density (mA/cm²)	pH	Saccharin (g/l)	Temperature (°C)	Time (Min)	Relative priority	Rank
pH = 1.5	20	1.5	0.25	45	30	0.163	4
Current Density = 5 mA/ cm²	5	3	0.25	45	30	0.314	1
Current Density = 40 mA/ cm²	40	3	0.25	45	30	0.165	3
Temperature = 70 °C	20	3	–	70	30	0.207	2
Temperature = 25 °C	20	3	–	25	30	0.151	5

Given to the mutual recognition of experimental results and AHP in this study, it is concluded that in similar cases, it is possible to carry out AHP before practical experiments. By implementing the AHP, electroplating alternatives that lead to the most favorable microstructure are identified. Because of the possibility of predicting the best alternative to achieve the ultimate goal, the researcher or industrialist can reduce experimental trial and error and reach the best operational alternative more quickly.

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