Research Article

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The Efficiency Analysis of Project Optimization Selection of AL_2O_3 Metallization

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ABSTRACT

The key factor of promoting a firm's competitive advantage is by means of sustainable innovation and meeting the low profit environment. For the development of new materials and new processes can promote effectiveness. Most of the research on process condition selection has been characterized by a basic approach to the problems. This study used a Taguchi orthogonal array to design the optimal experiment variables for reducing the test time and data envelopment analysis to integrate the chemicals control factor level, reaction time, reaction temperature for obtaining the efficiency selection in the process research management of thick electroless copper plating. After presenting the framework and formalization of method, the problem of searching for the best solution has been discussed. It could be constructed the product diversification to raise the research power and effectiveness of the firm's innovation by a cyclic research and development model.

Keywords: Competitive advantage; orthogonal array; efficiency selection; think electroless copper; data envelopment analysis; the optimal experiment variables.

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INTRODUCTION

Electroless copper plating is the most extensively used electronic chemical process. It is usually used for the metallization of different nonconductors, including PCB hole metallization and electromagnetic screens in wireless resistor housings. The electroless copper plating process is characterized by its low price, stable plating solution, good adhesion to nonconductors, good electrical conductivity, high ductility, excellent weldability, and electromagnetic screen effect. In the application of new materials, such as ceramic substrates, conductive cloth, polyimide varnish, polyimide films, and so on, the electroless copper plating process is required as the foundation for the application of metallization.

Electroless copper plating is divided into thin electroless copper plating[1-2] and thick electroless copper plating[3]. Thick electroless copper plating uses a formula similar to traditional electroless copper plating. Copper ions, a strong base, formaldehyde, and temperature are used as the motive power of the reaction, and time is used as the copper film thickness operating basis. However, the requirements for the copper film thickness are strict, and there are multiple and complex reaction conditions. In previous studies, five reaction condition factors, namely copper ions, NaOH, formaldehyde, reaction temperature, and reaction time were used; each conditional factor had four quality control factors [1,4].

LITERATURE REVIEW

Thick Electroless Copper Plating

Electroless copper plating refers to the process of using copper ions and a reduction agent [2]. According to the copper film thickness resulted from the reaction, there will be thin electroless copper plating, which generates 20~30 μin thick copper film and thick electroless copper plating, which generates 100~300 μin thick copper film.

In the first study of thin electroless copper plating, commercial electroless copper plating was used for plating through hole on PCB [5-6], PPO (polyphenylene oxide) based PCB were also studied [7], electronic modules [8-9], metallization process of

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non-metal materials [10], ABS resin[11][2, 3, 12, 13]. Previous studies have applied electroless copper plating on glass substrate , ABS resin (acrylonitrile-butadiene-styrene) [14], and polyimides (PI) [15]. A conducting fiber fabric was taken as an example [16-17], PET surfaces [18], SiC particle surfaces [14]. Previous studies applied electroless copper plating on ceramic surfaces, and found that the thick electroless copper plating formula uses copper ions, NaOH and HCHO as the motive power of reaction, and that the temperature and electroplating time are closely related to the copper film thickness [1, 4] [40]. According to the common redox equation and reaction empirical rate law of thin and thick electroless copper plating, the equations are expressed as follows:

Reducing reaction: $Cu^{2+}+2e^{-}\text{->}Cu$ (1)

Oxidation reaction: $2HCHO+4OH^{-}\text{->}2HCOO^{-}+H_2+2H_2O+2e^{-}$ (2)

Overall reaction: $Cu^{2+}+2HCHO+4OH^{-}\text{->}Cu+2HCOO^{-}+H_2O+H_2$ (3)

Previous studies have used EDTA-formaldehyde to determine the influence of the Cu^{2+}, OH-, and HCHO concentration on the deposition rate [19]. The empirical rate law of electroless copper plating is:

$$R=82\,[Cu^{2+}]^{0.78}\,[OH^{-}]^{0.02}\,[HCHO]^{0.13}\,[EDTA]^{0.02}\,\exp\left[\frac{17(T-323)}{T}\right] \quad (4)$$

where, R is the reaction rate and T is the reaction temperature (absolute temperature)

The Cu^{2+}, NaOH, HCHO, reaction temperature and reaction time are determined using procedures 1-4 and are used as input factors of the experimental conditions.

Orthogonal Array and Data Envelopment Analysis

DOE is a statistical method of arranging experiments and analyzing experiment data using fewer experiments over a shorter period and with lower cost [20].

DOE is divided into one factor at a time, full factorial experiments, and Taguchi's orthogonal array[21]. The full factorial experiment considers all possible factor combinations and pays attention to the interaction of various factors [22]. Taguchi's orthogonal array can integrate the merits and demerits of the aforesaid two DOE methods. Each quality control level in the orthogonal array must exist, and the combination frequency at all levels is the same [23-24]. In different industrial applications, the traditional experimental design concept and method have been changed successfully and applied to new domains, such as the sintering characteristic of TFT-LCD waste glass powder and reservoir sediment [25-27].

DEA is a linear programming method. Multi-input and multi-output efficiency evaluations can be handled simultaneously without presetting the weight or the influence of human-induced subjective factors. The process is objective and rational, and the measurement unit difference will not fail the evaluation [23, 28]. DEA evaluates the operating efficiency of enterprises or organizations. Charnes et al. [29] proposed the concept of using multiple inputs and multiple outputs to represent relative efficiency, which is represented by the first letters of their names (CCR.DEA). It is an optimal mathematical equation to calculate the efficiency value of each decision-making unit (DMU). Super CCR is a super-efficient model based on CCR [30-31].

DEA is the most effective method for evaluating efficiency. It can be used to assess the department performance of enterprises, government agencies, and corporation organizations, such as using DEA to study supply chain risk, simulation, and supply selection [32], supplier selection for low-carbon supply chains [33], and European countries' environmental assessments [34].

Actual cases of using an orthogonal array (OA) to simplify an experiment and DEA to select the experiment data are given below. Al-Refaie et al. [35] proposed an efficient way of using the super-efficiency technique of DEA in the Taguchi method to optimize the multiple quality characteristics in manufacturing, and turn blended PET fibers and nano TiO_2[36].

RESEARCH METHODS

Experimental Conditions

A total of 20 experimental designs were established according to the planned L_{20} orthogonal array conditions. A 5-inch aluminum standard ceramic plate was used, and after the wire was processed by a laser, the electroless copper plating reaction process of metallization was applied on the plate. [40]

Material: 5-inch Al_2O_3

Ra: 3.9 μm Ra: Surface roughness after laser processing

Power: 100% (19.36 W) IR laser

Speed: 30 times (225 sec)

Pitch: 0.06 mm

Chemicals: Electroless copper plating bath preparation (according to the orthogonal array) [38].

Process: Ultrasonic cleaning -> water washing -> activation -> water washing -> electroless copper plating -> copper metal film thickness/resistance (current) value test.

Orthogonal Array

This section explains the input factors influencing the electroless copper plating reaction, which were $[Cu^{2+}]$, the NaOH concentration [NaOH], the formaldehyde concentration [HCHO], and the reaction energy and reaction time. In addition, three or four level condition constraints were established. The output factors included the copper metal film thickness and current (Table 1).

Table 1. Factor levels

	Date/range	L1	L2	L3	L4
	Cu^{2+} (g/l)	1.8	2	2.2	2.4
	NaOH (g/l)	5	6	7	
Input	HCHO (g/l)	3	3.5	4	4.5
	Energy consumed (cal/ml)	50	55	60	
	The larger the copper film thickness (μm) is, the better is the output performance.				
Output	Energy consumed: absorbed energy (cal) for increasing the temperature of 1 ml bath solution by 1°C				

The DMU was evaluated by the multi-input multi-output efficiency of DEA. In an objective and rational evaluation, the relative efficiency value of each experimental combination was obtained. When multiple DMUs with an efficiency value of 1 are generated, one intercomparison can be performed by the target DMU and any other DMU, and the high efficiency ordering of DMU=1 is determined [39]. The optimum DMU selection was obtained from the evaluation.

EXPERIMENTAL RESULTS

An L_{20} orthogonal array was made to establish the experimental design, in which all possible parameter combinations were tested and related experimental results are recorded.

Orthogonal Array

By considering multiple input and output attributes, the relative efficiency of the DMU and plan were evaluated, and slack variable analysis and sensitivity analysis were used for group weight conversion to analyze the DMUs exceeding 1 (as shown in Table 2,3,4).

Super Efficiency Result

According to the data in the orthogonal array calculated by DEA, there were multiple combined conditions of DMU=1, therefore different relationships could not be expressed by an exact weight. As shown in Table 3, the evaluation result

Table 2. Data analysis

	X_1	X_2	X_3	X_4	X_5	Y_1	Y_2
Experiment	**Cu^{2+} (g/l)**	**NaOH (g/l)**	**HCHO (g/l)**	**Energy consumed (cal/ml)**	**Time (min)**	**Thickness (μm)**	**Current (A)**
1	1.8	5	3.5	50	80	3.2	393
2	1.8	6	4	55	90	4.3	458
3	1.8	7	4.5	60	100	5.1	500
4	1.8	5	5	50	110	4.8	478
5	1.8	6	3.5	55	80	4.1	407
6	2	7	4	60	90	5.1	500
7	2	5	4.5	50	100	4.6	458
8	2	6	5	55	110	5.1	500
9	2	7	3.5	60	80	4.7	478
10	2	5	4	50	90	4.5	440
11	2.2	6	4.5	55	100	5.3	524
12	2.2	7	5	60	110	5.8	579
13	2.2	5	3.5	50	80	3.8	423
14	2.2	6	4	55	90	5.2	524
15	2.2	7	4.5	60	100	5.7	550
16	2.4	5	5	50	110	5.5	524
17	2.4	6	3.5	55	80	4.5	440
18	2.4	7	4	60	90	5.3	524
19	2.4	5	4.5	50	100	5.4	524
20	2.4	6	5	55	110	5.7	550
Avg.	2.10	5.95	4.25	54.75	95.00	4.89	488.70

Table 3. Common efficiency.

DMU Name	Input-Oriented CRS Efficiency	∑λ	RTS
1	1.00000	1.000	Costant
2	0.96448	0.960	Increasing
3	1.00000	1.000	Costant
4	1.00000	1.000	Costant
5	1.00000	1.000	Costant
6	1.00000	1.000	Costant
7	0.98947	0.989	Increasing
8	0.96872	1.000	Increasing
9	1.00000	1.000	Costant
10	1.00000	1.000	Costant
11	0.98435	0.988	Increasing
12	1.00000	1.000	Costant
13	0.91317	0.842	Increasing
14	1.00000	1.000	Costant
15	1.00000	1.000	Costant
16	1.00000	1.000	Costant
17	1.00000	1.000	Costant
18	1.00000	1.000	Costant
19	1.00000	1.000	Costant
20	0.99385	1.023	Decreasing

Table 4. Super efficiency order

DMU No.	DMU Name	Input-Oriented CRS Super Efficiency	Optimal Lambdas with Benchmarks	
13	13	1.16667	0.833	14.000
4	4	1.07420	0.549	12.000
3	3	1.06918	0.481	4.000
19	19	1.05036	0.014	13.000
14	14	1.03704	0.457	9.000
9	9	1.03488	0.054	13.000
12	12	1.03249	0.043	3.000
15	15	1.02888	0.323	6.000
16	16	1.01852	1.019	19.000
18	18	1.01242	0.456	9.000
6	6	1.00294	0.098	3.000
20	20	0.99385	0.351	12.000
11	11	0.98136	0.417	12.000
17	17	0.97297	0.122	14.000
8	8	0.96226	0.481	4.000
2	2	0.96112	0.593	3.000
7	7	0.94350	0.455	4.000
10	10	0.94086	0.001	4.000
5	5	0.91525	0.058	3.000
1	1	0.86740	0.250	3.000

Table 5. Reaction rate

DMU	Cu^{2+}	NaOH	HCHO	Temp	Time	Thickness	A	Reaction rate(R)
4	1.8	5	5	50	110	4.8	478	0.805
3	1.8	7	4.5	60	100	5.1	500	0.839
19	2.4	5	4.5	50	100	5.4	524	1.025
14	2.4	6	4	55	90	5.2	524	1.206
9	2	7	3.5	60	80	4.7	478	0.929

indicated there were multiple combined conditions of DMU=1. Super CCR is the super efficiency model based on CCR, in which the target DMU=1 is compared with any other DMU so as to evaluate the high efficiency advantage difference. The input oriented super CCR model is expressed as follows:

$$\text{Max } \theta_o = \sum_{r=1}^{s} u_r \text{ x } y_{ro} \tag{5}$$

$$\text{st. } \sum_{i=1}^{m} V_i \text{ x } X_{ij} \geq \sum_{r=1}^{s} u_r \text{ x } y_{rj} \quad j = 1 \ldots n \quad j \neq 0 \tag{6}$$

$$\sum_{j=1}^{m} V_i \text{ x } X_{io} = 1 \tag{7}$$

$$V_i,\ u_r \geq \varepsilon > 0 \tag{8}$$

where, θ_O represents the efficiency of the DMU, x_{ij} represents the No. i input of the No. j DMU, y_{rj} represents the No. r output of the No. j DMU, v_i represents the weight of the No. i input variable, u_r represents the weight of the No. r output variable, and ε is the Archimedes number.

DMU14 and 19 had smooth conditional factors, the copper film thickness was better, and less time cost is used. DMU9 had smooth input factors, but the copper film thickness was smaller, and a higher temperature was required to maintain the efficiency value. DMU13 had an efficiency value = 0.91317 in the phase I DEA efficiency evaluation and was identified as an inefficient DMU.

Chemical Reaction Law

For the electroless copper plating reaction EDTA/HCHO system, the reaction rate law is expressed as Eq. (4):

$$R=82\text{x}[Cu^{2+}]^{0.78}\text{x}[NaOH]^{0.02}\text{x}[HCHO]^{0.13}\text{x}[EDTA]^{0.02}\text{x} \exp\left[\frac{17(T-323)}{T}\right] \tag{4}$$

where, R is the reaction rate constant and T is the reaction temperature.

The experimental reaction condition factors of the top five DMUs (4, 3, 19, 14 and 9) after super efficiency ordering were substituted into the reaction rate law to obtain R_{DMU4}=0.805, R_{DMU3}=0.839, R_{DMU19}=1.025, R_{DMU14}=1.206 and R_{DMU9}=0.929. The data showed that DMU14 had the highest reaction rate constant while DMU19 took second place, and that both DMUs met the super efficiency model prediction, as shown in Table 5.

According to the calculation results R=1.206 calculated under the reaction conditions of DMU14 had the maximum reaction rate constant value, Cu^{2+}=2.2 g/l, NaOH=6 g/l, HCHO=4.0 g/l of reaction tank bath, reaction temperature 55°C and reaction time 90 min were the optimal condition choices.

CONCLUSION

This study used an orthogonal array and super CCR-DEA to study the optimal condition selection of thick electroless copper plating in the metallization process of Laser plating copper on Al_2O_3, AlN [40].

It is can select the optimization condition and assess the efficiency of the project to build the firm's development model.

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