

Using fuzzy rule-based knowledge model for optimum plating conditions search

D S Solovjev¹, I A Solovjeva², Yu V Litovka², A A Arzamastsev¹, V P Glazkov³,
A A L'vov³

¹ Tambov State University named after G.R. Derzhavin, 33, Internacionalnaya, Tambov, 392000, Russia

² Tambov State Technical University, 106, Sovetskaya, Tambov, 392000, Russia

³ Yuri Gagarin State Technical University of Saratov, 77, Polytechnicheskaya, Saratov, 392000, Russia

E-mail: alvova@mail.ru

Abstract. The paper discusses existing approaches to plating process modeling in order to decrease the distribution thickness of plating surface cover. However, these approaches do not take into account the experience, knowledge, and intuition of the decision-makers when searching the optimal conditions of electroplating technological process. The original approach to optimal conditions search for applying the electroplating coatings, which uses the rule-based model of knowledge and allows one to reduce the uneven product thickness distribution, is proposed. The block diagrams of a conventional control system of a galvanic process as well as the system based on the production model of knowledge are considered. It is shown that the fuzzy production model of knowledge in the control system makes it possible to obtain galvanic coatings of a given thickness unevenness with a high degree of adequacy to the experimental data. The described experimental results confirm the theoretical conclusions.

1. Introduction

The choice of the optimal process conditions of the electroplating must eventually eliminate the manufacturing defect of product. The elimination of defective coatings will ensure the minimum cost per unit of output, which is the main criterion for evaluation of the galvanic process. The main causes of the defective product are its appearance, uneven coating thickness, coating porosity and adhesion strength of the coating to substrate. Receipt of galvanic coatings with the desired characteristics is associated with processing and analyzing large amounts of experimental and statistical information. It is necessary to select and control the modes of electrolysis and the composition of the electrolyte. In order to realize the optimum conditions for the application of galvanic coatings on the product, the technologist should optimize the configuration of tubs, anodes and protective screens. Modeling of technological processes of producing galvanic coatings with the desired characteristics is discussed in numerous papers. A mathematical model is considered in [1], which takes into account the influence of geometrical and electrochemical factors on the coating process. A mathematical model for the



dynamics of mixing and the rate of electrolyte renewal in the contact area is described in [2]. The paper [3] presents a mathematical model describing the thickness distribution on the product with the use of fractals is. However, the search for optimum conditions of plating on a product belongs to a class of poorly structured and multi-criteria problems, in some cases, generally not subjected to formalization. Therefore, the optimal condition in problems of this class can be found only with the combination of experience, knowledge and intuition of the decision-maker (DM). To search for optimal conditions, methods of data mining, considerations based on product knowledge models, simulation modeling, evolutionary computation and genetic algorithms, neural networks, situational analysis, and cognitive modeling can be used. These methods are implemented when special systems of decision support (DSS), based on modern computer technologies, are designed and developed.

The use of an artificial neural network is described in the work [4] to predict the rate of the coating thickness growth on the output product surface. The paper [5] discusses the choice of metal plating from the point of view of economic, physical-mechanical, technological and ecological criteria based on the method of analysis of hierarchies. The work [6] compares the effectiveness of genetic algorithms with statistical regression ones with respect to the task of identifying factors that have the greatest influence on characteristics of galvanic coatings. Nevertheless, at present there are no works on the optimal conditions search for application of electroplating coatings on a product, which is based on considerations concerning knowledge production models.

The aim of the work is to find the optimal conditions for the application of electroplating coatings on the product based on considerations that using the production models of knowledge excludes defective products.

2. Searching for optimal plating process conditions: problem statement

The problem under consideration is optimum conditions search for electroplating process, which reduce the uneven distribution of electro-galvanic coating thickness on the product surface. The uneven thickness of the coating may be evaluated by criteria proposed by L.I. Kadaner in the book [7]. The unevenness of the plating is determined by the ratio of the mean thickness $\bar{\delta}$ distribution of deposited metal on the surface S_c of the product to specified minimum thickness δ_{\min} :

$$R = \bar{\delta} / \delta_{\min} , \quad (1)$$

where δ_{\min} , $\bar{\delta}$ are the minimum and average thickness of the coating.

In turn, the average thickness of the coating can be calculated from the law of M. Faraday:

$$\bar{\delta} = \frac{E}{\rho} \cdot \eta(i, t, C_1, C_2, \dots, C_j, \dots) \cdot i \cdot T \quad (2)$$

where E is the electrochemical equivalent of the metal; T is the duration time of the electroplating process; ρ is the density of the coating metal; η is the amount of metal at the output under the action of electric current; t is the electrolyte temperature; i is the current density; C_j is the concentration of the j -th electrolyte component. As a rule, η is obtained by the processing of the experimental data and it depends on i , t , and values of C_j .

It follows from (2) that the current density and temperature of the electrolyte have a main influence on the average value of coating thickness. It is established, that the temperature increase in the electrolytes having monotonous polarization curve, increases the conductivity of the solution. On the contrary, scattering ability decreases with temperature increasing. According to J. Tafel equation, the current density can influence both positively and negatively on scattering ability. If at high current densities the metal output under the electric current action is lower than at low current densities, this ratio favorably affects the scattering ability. Therefore, in order to obtain the optimal operating parameters it is necessary to find the current density i^* and electrolyte temperature t^* , which deliver the minimum value of criterion (1) characterizing the uneven thickness of the product coating.

3. Development of rule-based model for optimal plating process conditions

The conventional mathematical model of the plating process was described in [8] where it consists of three equations, one of which is partial differential equation, and three boundary conditions on the boundaries “electrolyte – insulator”, “electrolyte – anode”, and “electrolyte – cathode”.

The solution of this optimization problem is sought using the efficient algorithms for nonlinear programming. Moreover, it is nontrivial and time-consuming task. In this regard, to solve this problem, it is proposed to use the fuzzy production model of knowledge [9]. The current density “ i ” and electrolyte temperature “ t ” will serve as input linguistic variables for this model. The following terms of membership functions are defined for variable “ i ”: $\mu_1(i)$ – “low”; $\mu_2(i)$ – “average”; and $\mu_3(i)$ – “high”. Proceed in the same way for the variable “ t ” is: $\mu_1(t)$ is “low”; $\mu_2(t)$ – “average”; $\mu_3(i)$ – “high”. Changes in the density of the current “ Δi ” and the electrolyte temperature “ Δt ” will serve as the output linguistic variables. Variables are terms membership functions: $\mu_1(\Delta i)$ – “decrease”; $\mu_2(\Delta i)$ – “do not change”; $\mu_3(\Delta i)$ – “increase”; $\mu_1(\Delta t)$ – “decrease”; $\mu_2(\Delta t)$ – “do not change”; $\mu_3(\Delta t)$ – “increase”. The ranges of the linguistic variables and the specific form of the membership functions of terms depend on the metal coatings and electrolytes used for electroplating processes. A set of membership functions determines rule-based model the search of operational parameters of electroplating in terms of fuzzy logic.

The base of knowledge in rule-based model contains a system of rules, based on conditional statements of the type E. Mamdani, written in the form “IF ... THEN ...”. The system of rules generates the output values of the variables, based on the values of input variables in the following way:

- 1) IF i = “high” And t = “low” THEN Δi = “decrease” AND Δt = “increase”;
- 2) IF i = “high” And t = “high” THEN Δi = “decrease” AND Δt = “decrease”;
- 3) IF i = “average” And t = “average” THEN Δi = “do not change” AND Δt = “do not change”;
- 4) IF i = “high” And t = “average” THEN Δi = “decrease” AND Δt = “do not change”;
- 5) IF i = “average” And t = “high” THEN Δi = “do not change” AND Δt = “decrease”;
- 6) IF i = “low” And t = “average” THEN Δi = “increase” AND Δt = “do not change”;
- 7) IF i = “average” And t = “low” THEN Δi = “do not change” AND Δt = “increase”;
- 8) IF i = “low” And t = “NOT high” THEN Δi = “increase” AND Δt = “do not change”;
- 9) IF i = “NOT high” And t = “low” THEN Δi = “do not change” AND Δt = “increase”.

The defuzzification operator for this system of rules is proposed to be carried out using the “center of gravity” method, which is the most suitable technique for solving optimization problems:

$$\Delta i = \frac{\int_{\Delta i_{min}}^{\Delta i_{max}} \Delta i \cdot \mu^{\Sigma}(\Delta i) \cdot d\Delta i}{\int_{\Delta i_{min}}^{\Delta i_{max}} \mu^{\Sigma}(\Delta i) \cdot d\Delta i} \quad \text{and} \quad \Delta t = \frac{\int_{\Delta t_{min}}^{\Delta t_{max}} \Delta t \cdot \mu^{\Sigma}(\Delta t) \cdot d\Delta t}{\int_{\Delta t_{min}}^{\Delta t_{max}} \mu^{\Sigma}(\Delta t) \cdot d\Delta t} \quad (3)$$

where Δi_{min} , Δi_{max} , Δt_{min} , Δt_{max} are the ranges of the output variables; μ^{Σ} is the final membership function of a fuzzy set of the output variable.

4. Block diagram of electroplating process control system

In order to search the optimal conditions, the electroplating process control systems basing on: a) a traditional mathematical model and b) a fuzzy rule-based model are considered. To do this, the galvanic process is represented as a control object, allocating the finite set of input $x(\tau)$ and output $y(\tau)$ coordinates as well as external perturbation $f(\tau)$ and control $u(\tau)$ influences.

The following information at the input $x(\tau)$ of the control object: the configuration of the anodes S_a and the workpiece S_c , the quality H of the preliminary surface preparation of this workpiece. The output $y(\tau)$ of the control object is information about the workpiece appearance, unevenness of the coating thickness, porosity and adhesion strength of the coating to the substrate.

The control action $u(\tau)$ on an object is a combination of the following parameters: 1) the current density i on the product surface; 2) the temperature t of the electrolyte; 3) the j -th component

concentration C_j of the electrolyte; 4) pH of the electrolyte; 5) the level L of the electrolyte solution; 6) the number N of product; and 7) their location F in the galvanic bath.

Among the measurable and non-measurable disturbances $f(\tau)$ are: the presence of electrolyte impurities P , the surface defects D of the product, ablation of Q the electrolyte from bath on surface of the product, evaporation E of the electrolyte from the bath, interrupted electrical contact B in the coating process and the experience O of the operator of galvanic lines. External disturbances are stochastic in nature, but their effect on the galvanic process can be reduced or prevented. It is necessary to pay attention to the choice of electroplating equipment for the preparation and application of coatings and maintenance of equipment. Periodic analysis of the composition of electrolytes is required. Depending on the operation conditions of the product, it is necessary to improve the control of surface of detail. One should also conduct timely training and refresher training operators of electroplating.

Usually in traditional control systems (Figure 1a), mathematical models are used in combination with optimization algorithms to generate the $z(\tau)$ commands to the control devices (power supplies, heating elements, pumps for correction of electrolyte, mechanisms for the swing rods, the motor-reducers, positioning of suspension, etc.).

A block diagram of a controller using the knowledge-based decision support systems (DSS), is shown in Figure 1b. This DSS should form recommendations for decision-makers $v(\tau)$ to eliminate a specific type of defect based on information about the input and output coordinates, as well as the control action. Recommendation $v(\tau)$ not only the rules with the exact values of the input and output variables, but also fuzzy values. The presentation of these recommendations, $v(\tau)$ can be the following: "to decrease/increase the acidity of the electrolyte," "to decrease/increase the electrolyte level", "increase/decrease surface anodes" "clean the electrolyte from impurities", "install protective screens", "to improve the preparation of surface", "troubleshooting electrical", etc. The efficiency of the conventional control system and control system based on DSS can be evaluated by comparing the results of their work with the experimental results using typical examples.

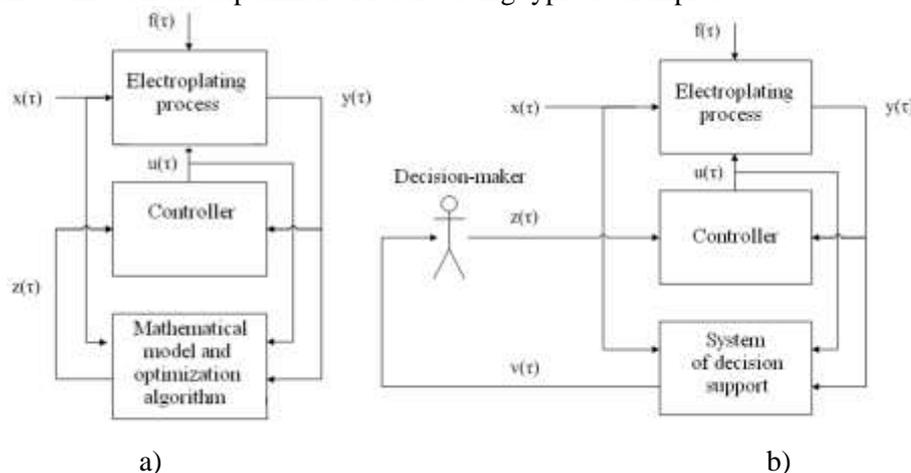


Figure 1. The block diagrams of a classical control system (a) and system of decision-making support (b)

5. Materials and methods

One of the most common electroplating processes, i.e. nickel-plating in sulfate electrolyte, is considered. High concentrations of nickel salts in the sulfate electrolyte make it possible to increase the density of the cathode current and, as a result, increase the process productivity. The most common composition of sulfate electrolyte for galvanic process are the following, g/l: $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$ 240 – 250, NaCl – 22.5; H_3BO_3 – 30. Nickel plating is carried out at temperatures from 50°C to 60°C and the range of current densities from 0.1 A/dm^2 to 10 A/dm^2 . Constants for calculating the equations of conventional mathematical models have the following meanings: electrochemical equivalent $E = 1.024$

g/A·h; the density $\rho = 8900 \text{ g/dm}^3$. The functions of anode and cathode polarization as well as the metal output under the electric current action for nickel plating in sulfate electrolyte at current concentrations of the components of electrolyte and its acidity pH = 4.5 to 5.5 were taken from the article [10].

For the control system using DSS, a triangular form is chosen as the type of membership functions of the term sets for input variables and bell-shaped type membership functions of the term sets for the output variables correspondingly:

$$\mu_m(v; a; b; c) = \begin{cases} 0, & v \leq a \text{ and } v > c; \\ \frac{v-a}{b-a}, & a < v \leq b; \\ \frac{c-v}{c-b}, & b < v \leq c; \end{cases} \quad \mu_m(w; d; g; h) = \left(1 + \left| \frac{w-h}{d} \right|^{2g} \right)^{-1}, \quad (4)$$

where a and c designate the interval of fuzzy set; b is the nucleus; m is the function number; v is the input variable; d, g, h are the concentration coefficients of slope and maximum of the membership function; w is the output variable.

For the current density (Figure 2a) and the temperature of the electrolyte (Figure 2b) of the membership function are of the form: $\mu_1(i; -; 0; 4)$, $\mu_2(i; 2; 5; 8)$, $\mu_3(i; 6; 10; -)$, $\mu_1(t; -; 50; 54)$, $\mu_2(t; 52; 55; 58)$, $\mu_3(t; 56; 60; -)$. Membership functions for change of the current density (Figure 2c) and the temperature of the electrolyte (Figure 2d) have the following form: $\mu_1(\Delta i; 0.2; 1; -1)$, $\mu_2(\Delta i; 0.2; 1; 0)$, $\mu_3(\Delta i; 0.2; 1; 1)$, $\mu_1(\Delta t; 0.38; 0.9; -2)$, $\mu_2(\Delta t; 0.38; 0.9; 0)$, $\mu_3(\Delta t; 0.38; 0.9; 2)$.

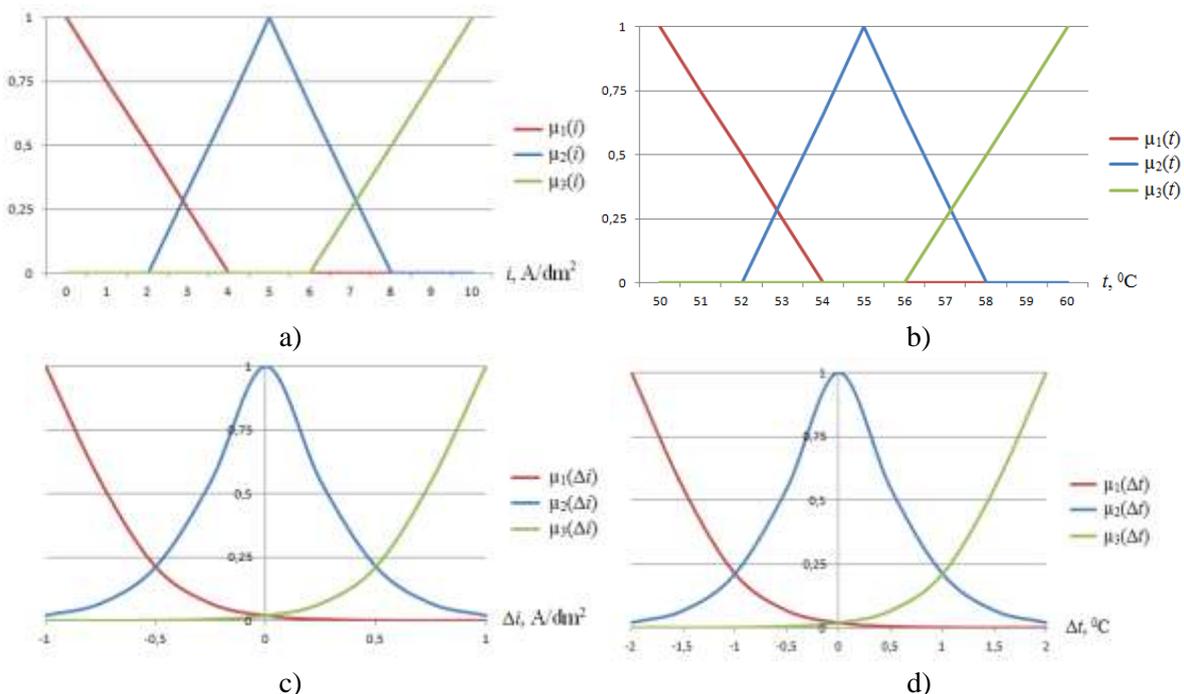


Figure 2. The block diagrams of a classical control system (a) and system of decision-making support (b)

6. Results and discussion

Deviation of the experimental measurements of average thicknesses of coatings from those calculated by traditional mathematical models $\Delta\delta_{exp}^{mm}$ and fuzzy rule-based model $\Delta\delta_{exp}^{fl}$, are depicted in Fig. 3.

For T-shaped workpiece the calculation error for fuzzy rule-based model is 2% more than the traditional model. In other cases (for V - and Z-shaped workpieces) calculation of fuzzy rule-based model gave a lower error (5% and 3%). Thus, for some forms of workpieces more accurate average value of the thickness of the coating is obtained compared with a conventional mathematical model.

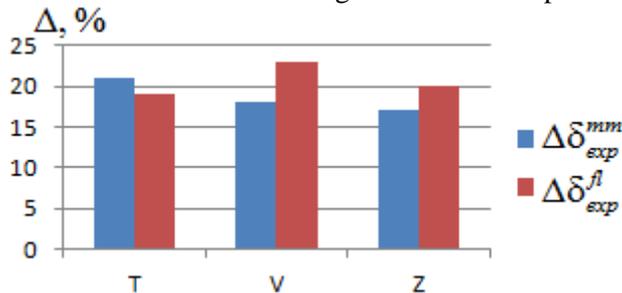


Figure 3. The comparison results of the experimental deviations of the mean coating thickness values from the predicted values for the studied T-, V - and Z-shaped forms of workpieces

7. Conclusion

Recently, the intellectualization of the stages of modeling of technological processes of producing galvanic coatings with the desired characteristics has been increasingly demanded by the task. It is shown in the work, that the receipt of galvanic coatings with a given uniformity is possible not only with the use of control systems based on traditional mathematical models but also fuzzy rule-based models with a high degree of adequacy. To improve the accuracy of calculation in traditional mathematical models, it is necessary to remove assumptions, to increase the number of equations and the number of grid nodes along each of the coordinates. Improving the accuracy of calculation in fuzzy rule-based model to be much simpler task: it will require only a change in form of membership functions of terms, the increase in their number and the number of rules of inference.

References

- [1] Robison M R and Free M L 2014 Modeling and experimental validation of electroplating deposit distributions from copper sulfate solutions *ECS Transactions* **61** 27-36
- [2] Filzwieser A, Hein K and Mori G 2002 Current density limitation and diffusion boundary layer calculation using CFD method *J. Minerals, Metals & Materials Society* **54(4)** 28-31
- [3] Jack G Z, Zongyan H and Jian Guo 1999 Fractal growth modeling of electrochemical deposition in solid freeform fabrication *Proc. 10th Solid Freeform Fabrication Symp. (Modeling)* (Austin: University of Texas) chapter 1 pp 229-238
- [4] Sánchez L F, Vilán V J A, García N P J and Coz D J J 2010 The use of design of experiments to improve a neural network model in order to predict the thickness of the chromium layer in a hard chromium plating process *Mathematical and computer modelling* **52(7-8)** 1169-1176
- [5] Kaoser M M, Mamunur R M and Sharif A 2014 Selecting a material for an electroplating process using AHP and VIKOR multi attribute decision making method *Int. Conf. on Industrial Engineering and Operations Management (IEOM 2014)* ed M A Hossain (Bali) chapter 1 pp 834-841
- [6] Ossman M E, Walaa S and Eltaweel Y 2010 Linear Genetic Programming for Prediction of Nickel Recovery from Spent Nickel Catalyst *American J. of Eng. and Applied Sciences* **3(2)** 482-488
- [7] Kadaner L I 1961 *The uniformity of electroplated coatings* (Kharkov: Kharkov State University)
- [8] Subramanian V R and White R E 2000 Simulating Shape Changes during Electrodeposition: Primary and Secondary Current Distribution *J. Electrochem. Soc.* **149(10)** 498-505
- [9] Phukon L J and Baruah N 2015 Design of fuzzy logic controller for performance optimisation of induction motor using indirect vector control method *Int. J. of Electrical, Electronics and Data Communication* **3(2)** 72-78
- [10] Kudryavtsev N T 1975 *Applied electrochemistry* (Moscow: Chemistry)