Simulation of Thickness Distribution of Electrodeposition Coating

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An electric current distribution analysis program "Electroplating Pilot System" (EPPS) was developed, and has been sold. As an expansion of EPPS, a new program using Finite Element Method (FEM) that allows to calculate thickness distribution of electrodeposition coating was developed. By introducing new thickness calculation parameters that consider special characteristics of electrodeposition coating, practical thickness calculation precision was possible to obtain. The experiment method to obtain thickness calculation parameter and parameter determination method based on experiment data were indicated. Also, constant voltage coating test on flat plate and analytical result of the test were compared. Both total current and thickness on each test matched well.

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Introduction

Electrodeposition coating is commonly used as an undercoat for automobile body due to its excellence in throwing power and corrosion protection. However, it is difficult even coating due to the body's unique design. It is often obtained insufficient thickness film on the body such as inner box - sharped corners. Film thickness is usually evaluated by measuring electrodeposition coating on the body section sliceda sample auto body, and slicing each body section for measurement. The sample coating is usually done during the final stage of car designing. Thus, if thickness distribution using electrodeposition coating can be simulated during the body designing stage, sections that are difficult to coat can be determined and modified at an earlier point in time. This will reduce the number of sample coating tests required for the auto body, which will eventually lead to a shorter development period, cost reductions, and higher quality. In order to achieve these objectives (cost reductions, etc.), research on thickness distribution simulation of electrodeposition coating has been conducted.[1,2]

An electric current distribution analysis program "Electroplating Pilot System" (EPPS) was developed, and has been distributed.[3,4] A new program using Finite Element Method (FEM) was developed as an expansion of EPPS. This program enables one to calculate the thickness distribution of electrodeposition coating. The introduction of new calculation parameters that include special characteristics of electrodeposition coating made practical thickness calculation precision possible to obtain. In this report, the experimental method used to obtain thickness calculation parameters as well as parameter determination methods based on experimental data were indicated. Also, the analytical results of the stationary voltage coating tests on a flat plate were compared to prove the reliability of the analysis.

Analysis Model

The following reaction Equation [1] and [2] takes place on the cathode surface during cation electrodeposition coating:

$$2H_2O+2e^-=H_2+2OH^- \quad [1]$$
$$RNH_3^+ + OH^- ? RNH_2 + H_2O \quad [2]$$

Here, RNH_3^+ represents the paint particle. When using cation paint, water electrolysis occurs on the cathode electrode surface and forms OH^- (Equation?[1]). Then, when OH^- reaches a certain density, it reacts with the paint particle inside the solution and forms water (Equation 2). From this reaction, the paint particle that lost charge deposits on the electrode surfaces as the coating film. Also, some OH^- near the electrode disappears by time due to diffusion and the electrophoresis influence.[5,6]

In electrodeposition coating, circulated current determines deposited film, being similar to insulator(˜10^{-7}S/m). The film works as a resistant, and the current gradually decreases as thickness increases. The analysis of electrodeposition coating is unstational problem because the current changes by time section. If time section can be discreted by difference method, the stationary current field problem of conductors can be focused. Thus, assume that the Laplace equation [3] forms when applying the unknown number potential φ to paint, thickness, and cathode. The Laplace equation can be analyzed by using the simulation method such as FEM.

$$?^2?=0 \quad [3]$$

Thickness calculation is easy for electroplating because Faraday's law holds between electricity and reaction, and there are certain correspondence in electricity and the weight of deposited metal. If the relation between electricity and deposition weight is clear, film thickness at a particular time can be determined by applying the relation of Equation [3], and the relation of electricity and deposition weight in Newton-Raphson method for repetitive calculation.

In electrodeposition coating, Faraday's law can be applied to electricity and OH^- ion production amount by Equation [1]. However, the coating film is formed by the reaction of OH^- ion and paint particle described in Equation [2], thus the relation of electricity and the film production amount is not clear. To perform an analysis of electrodeposition coating, the Laplace equation that determines current flow by potential distribution (Equation [3]), and the diffusion equation of OH^- ion and paint particle needs to be simultaneously calculated. However, with existing computers, it is impossible to proceed with analysis and obtain results that can be applied for practical usage.

In order to obtain simulation results for practical usage, it is necessary to determine the relationship between electricity and the deposition weight of film through experiments. If this relation is proven, thickness distribution for electrodeposition coating can be determined as same as thickness distribution in electroplating.

Parameter Determination of Thickness Calculation

Stationary Voltage Coating Test. - To clarify the relationship between electricity and film deposition weight, an experiment of stationary voltage coating on a flat plate was conducted using the cell shown in Fig. 1 under the conditions described in Table 1. Figure 2 shows the time chart of coating voltage. Temperature and agitation are also set at the same condition as the actual coating plant that analysis will occur.

The experiment will measure current, electricity, and deposition weight at 50, 150, and 250V, with coating time at 60, 120, and 180 sec.

Determination of Coating Equivalent. - Table 2 describes the measurement data of electricity and deposition weight that are changed into values per unit area. A regression analysis is applied to electricity and deposition weight after 180 sec at 50, 150, and 250V. Figure 3 shows the results of the regression analysis. The results show that deposition weight of film correlates with electricity. The correlation coefficient here is the deposition weight per 1C, and this is called the coating equivalent. Also, the crossing point of the X axis and the regression line on the graph is the point in which electricity does not relate to film deposition within 180 seconds of coating time. The value that does not relate to film deposition is called invalid deposition electricity at 180 sec.

Determination of Diffusion Consumed Current Density and Starting Deposition Electricity. - The film deposition electricity on Table 2 is the value of coating equivalent divided by deposition weight at each coating time. The invalid deposition electricity on Table 2 is the difference of electricity and film deposition electricity at each coating time. Next, regression analysis is applied to invalid deposition electricity and coating time at each voltage shown (See Table 2). The increased electricity of invalid deposition electricity per time unit is called diffusion consumed electricity. Also, the Y value in regression analysis is called starting deposition electricity. Table 2 shows the diffusion consumed current density and the starting deposition electricity at each coating voltage. There was a slight tolerance in diffusion consumed current density at each coating voltage, but mean value of 2.42 in Table 4 is within ±5% range. From mean diffusion consumed current density, the diffusion consumed electricity at 180 sec was calculated. Difference of this value and invalid deposition electricity at 180 sec was determined as starting deposition electricity of this paint (Table 4).

Determination of Film Conductivity. - Table 3 shows the calculation method used for film conductivity. The current on the table indicates the current of each coating time at each voltage. Film density is set at $1400 kg/m^3$ taken from deposition weight in Table 2. Film voltage is the voltage on film, and it is the value of the potential decrease in paint subtracted from coating voltage. The potential decrease in paint is calculated by setting resistance value of paint at 53.6Ω (profile: 100x160mm, length: 150mm, conductivity: 0.175S/m) and multiplying it by current value. Each conductivity had a maximum tolerance of ±10% to mean total value. In this analysis, all mean conductivity calculated was used.

Analysis and Discussion

Analysis. - In the analysis, the cell used in the experiment was converted into a model to apply mesh plot using the tetrahedron element (Fig. 4). Only half of the total cell is needed for modeling. Elements of the figure. consists of a metal (cathode) , film, over potential, paint, and anode. The cathode element uses the solid element to match the thickness with metal material, and 0 thickness film and over potential elements are placed outside the cathode element. Size of analysis model is nodal points of 5710 and element of 19838. Table 4 shows the analysis parameter. The time interval for repetitive calculation is set at 0.5, 1, 2, 3, 5, 10, and 20 sec, and at 180 sec it completed repetitive calculation of 84 times. The time required for this calculation was about 41 sec on PC with Pentium 4 2.0GHz processor.

Comparison. - The comparison graph of the total current time change experiment and its analysis result is shown on Fig. 5, and the comparison graph of thickness change by time is shown on Fig. 6. In comparison with total current, three voltage settings and earlier current peak values matched well, and although analysis is slow, current peak time almost matches. Also, there is a huge difference after 30 sec at 250V, current value matches at three voltages at the end. In comparison with thickness distribution, there is a slight difference between experiment and analysis results at 60 sec, but they match at 180 sec

Conclusion

The FEM program that calculates thickness distribution of electrodeposition coating was developed. Assuming that the Laplace equation forms with potential being unknown number for cathode, film, over potential, and paint, thickness calculation equation that considers deposition function was complied. By doing so, practical thickness calculation precision was possible to obtain. For thickness calculation equation, new parameters such as current value that corresponds to consumption of OH^- ion diffusion, and electricity that corresponds when OH^- ion reaches certain density were introduced. By separating electricity that relates and does not relate to film deposition, coating equivalent that is the deposition amount of film per 1C is determined as constant number. Also, the determination method of these thickness calculation parameters was changed into an equation.

The stationary voltage coating test on flat plate was analyzed, experiment value and analysis value were compared, and high analysis accuracy of thickness was confirmed.

Acknowledgments

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Table 1. Conditions of electrodeposition coating

Cell	100x160x250mm?
Agitation	Yes
Voltage	50?150?250V
Temperature	28?
Coating Time	60?120?180sec
Interval	150mm
Cathode Area	70x100mm
Area Difference	1/2 (anode/cathode)

Table 2. Measurement data and regression analysis

Voltage (V)	Time (sec)	Current density (A/m^2)	Electricity (C/m^2)	Deposition weight (kg/m^2)	Film deposition electricity (C/m^2)	Invalid deposition electricity (C/m^2)	Diffusion consumed current density (A/m^2)	Starting deposition electricity (C/m^2)
50	60	3.36	393	0.0050	71.6	321.3		
	120	2.79	579	0.0067	94.7	483.9		
	180	2.50	736	0.0076	107.8	627.9	2.55	171.1
150	60	5.29	521	0.0131	186.2	335.2		
	120	3.29	764	0.0186	265.4	498.9		
	180	2.71	936	0.0223	316.9	618.8	2.36	200.7
250	60	5.50	657	0.0216	307.7	349.5		
	120	3.71	929	0.0294	418.9	509.7		
	180	3.00	1100	0.0331	471.2	628.8	2.33	216.7

Table 3. Determination of coating film conductivity

Voltage (V)	Time (sec)	Current (mA)	Film thickness (µm)	Film voltage (V)	Film resistance (kΩ¥cm^2)	Film conductivity? (S/m)	Mean Film conductivity (S/m)
50	60	47	3.6	47.5	141	2.54x10^{-7}	
	120	39	4.8	47.9	172	2.76x10^{-7}	
	180	35	5.4	48.1	193	2.81x10^{-7}	
150	60	74	9.3	146.0	276	3.38x10^{-7}	
	120	46	13.3	147.5	449	2.97x10^{-7}	2.98x10^{-7}
	180	38	15.9	148.0	545	2.92x10^{-7}	
250	60	77	15.4	245.9	447	3.45x10^{-7}	
	120	52	21.0	247.2	666	3.16x10^{-7}	
	180	42	23.7	247.8	826	2.86x10^{-7}	

Table 4. Parameters for calculations

Name	Value
Paint conductivity	0.175 S/m
Film conductivity	2.98×10^{-7} S/m
Coating equivalent	7.02×10^{-5} kg/C
Invalid deposition elec. at 180 sec	625.2 C/m^2
Diffusion consumed current density	2.42 A/m^2
Diffusion consumed elec. at 180 sec	435.6 C/m^2
Starting deposition electricity	189.6 C/m^2
Film density	1400 kg/m^3
Coating voltage	50,150,250 V
Coating time	180 sec

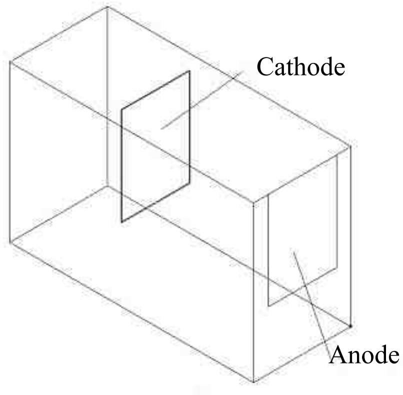


Fig. 1. Structure of experimental cell

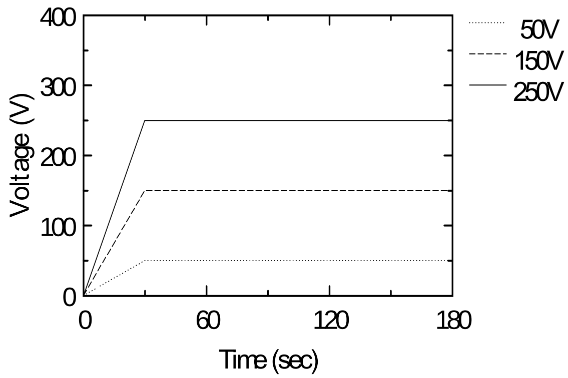


Fig. 2. Time chart of coating voltage

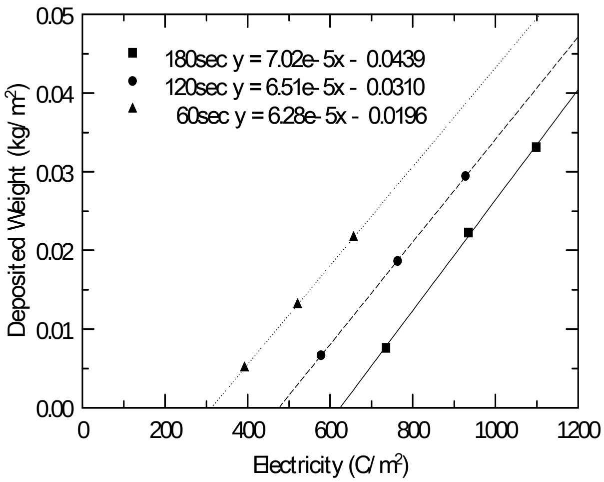


Fig. 3 Relation between the electric quantity, and deposition weight

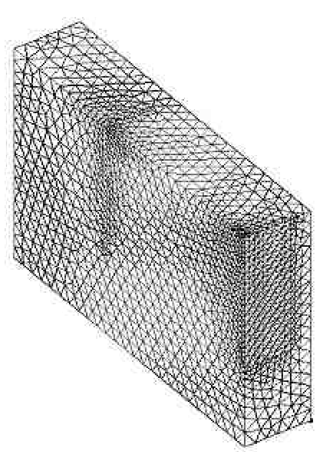
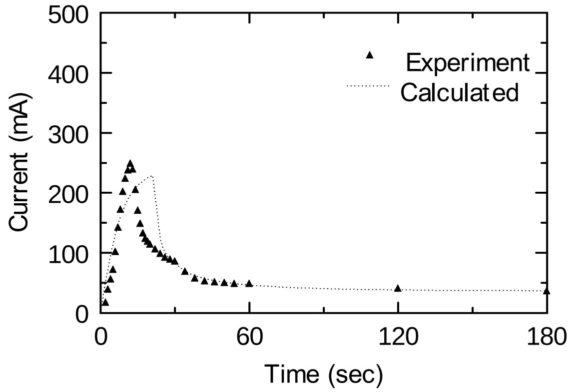
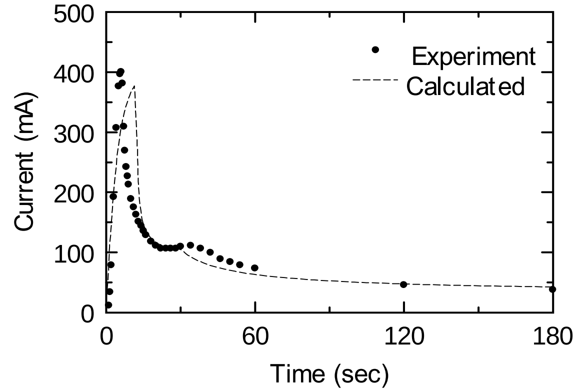


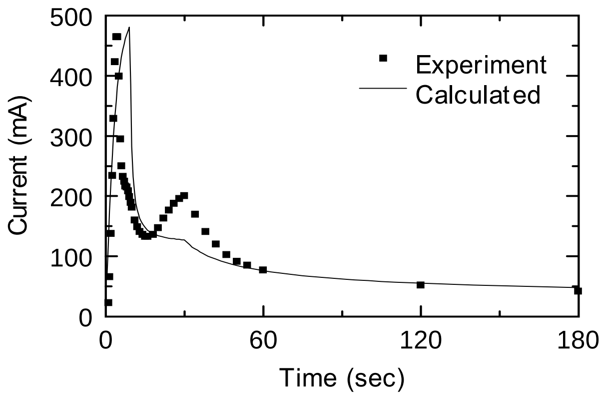
Fig. 4. Mesh division figure for calculations



a) Coating voltage 50V



b) Coating voltage 150V



c) Coating voltage 250V

Fig. 5. Comparison of calculated and experimental data of total current

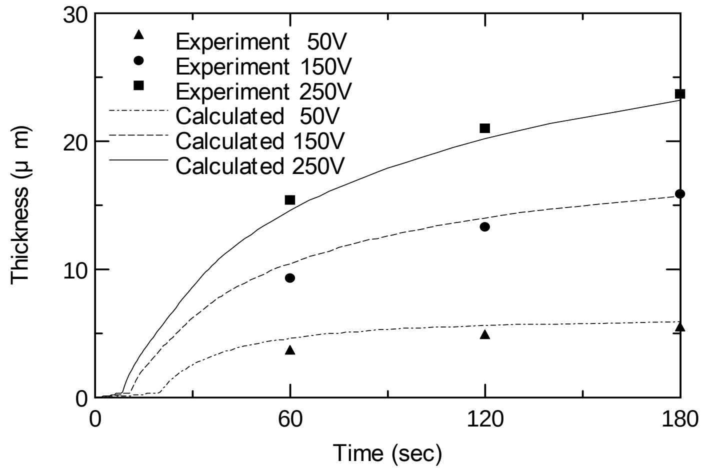


Fig. 6. Comparison of calculated and experimental data of the deposit thickness