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論文

Parameter Design of Film Forming Process to Control Spatial Distribution of Film Thickness

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【Abstract】

In the manufacturing process of any mechanical parts with spatially varied characteristics, controlling a characteristics distribution is important depending on its intended use. In the electroplating process, it is desirable to form a thin film with different thickness on different local positions on the base material. Therefore, it is necessary to achieve a specific profile of film thickness distribution. Although the conventional robust parameter design have been used to make a uniform film, it is difficult to design a custom profile of film thickness distribution under various constraints. Considering this situation, we propose a parameter design method to control a spatial distribution in a custom profile with a parameter design. Three regression parameters corresponding to feature quantities of a distribution are designed as multi-objects. The effect of the method will be verified for an electric plating process as a case study. Also an application to control the profile based on this approach will be introduced.

Keyword：Design of experiments, Robust parameter design, Depiction variables, Electroplating process, Distribution profile feature quantities

1. Introduction

1.1. Purpose of this study

In the manufacturing process of mechanical parts comprising the complex characteristics varying spatially, controlling not only just the average but a characteristics distribution has become an important. Usually, it is achieved with a thin film deposited on a base material. Performing a uniform film thickness is insufficient to meet the target specification of the mechanical part depending on requirements for a final product. By the shape and intended use of the parts, a specific profile of film thickness distribution is required depending on its intended use.

For electroplating process (Lawrence J. D., (2014)) we discuss in this study, plating film is responsible for various surface functionalities simultaneously, including mechanical strength such as abrasion resistance, electrical characteristics such as electrical conductivity, chemical characteristics such as corrosion resistance, physical characteristics and optical characteristics and so on. To achieve a specific spatial distribution of the functionalities, it is desirable to form a thin film with different specifications at different local positions on the base material. Therefore, it

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is necessary to achieve a specific distribution profile of film thickness. For example, a thick film at the local area where it contacts with another mechanical part is preferred over the other area to improve the wear resistance against a part with sliding movement. On the other hand, it is necessary to strictly control the film thickness at the fitting portion with the matching parts. Furthermore, when corrosion resistance of a plating film along the edge area of a plate-shaped part is important, the center of the film thickness distribution should be located at the center of the base material for the thickness variation reduction. In addition, if in the case that film thickness at the edge area is not important for the product specification, it is necessary to minimize it for production cost reduction. Based on consideration about the above situation, we propose a parameter design method to control a spatial distribution of characteristics such as film thickness in a custom profile and verify the effect of the method using an electric plating process as a case study.

1.2. Previous research

Although conventional robust parameter design can be carried out to uniform a characteristics distribution such as thickness of a plating film, it is difficult to achieve a custom distribution under various constraints. To control a distribution profile, several methods have been proposed, in quality engineering (Phadke (1989), Taguchi et al. (2004)), we may be able to match an input-output relation of product characteristics to an ideal relation using standard S/N ratio (Miyakawa (2000)). Therefore, by regarding the position on the base material as a noise factor, it may be possible to adjust a distribution profile of film thickness into an ideal profile. However, as we pointed out in Mitsui and Takahashi (2014) and Mitsui (2015), a quality engineering approach might fail in the situation that we could not find a robust solution where negotiation between stakeholders are required to find a point of compromise as a bottom line.

The statistical modeling approach (Myers, Montgomery and Anderson Cook (2009), Wu and Hamada (2009), Tsubaki, Nishina and Yamada (2007), Kawamura and Takahashi (2013)), in contrast to quality engineering approach, might be helpful as in the situation described the above, because it handles design factors quantitatively rather than qualitatively. This approach is also useful for multi-object optimization (Joseph and Wu (2002), Joseph (2003)). As a method to achieve a custom distribution profile, it can be applied robust parameter design with the statistical modeling method Takahashi (2012a) proposed. In that method, a standard profile has been defined as an ideal distribution or a theoretical distribution. Takahashi (2012b) also proposed another approach where a local film thickness at the position on the base material is regarded as independent characteristics. A multi-objective parameter optimization is carried out to find solutions meet with target values to achieve specific distribution profile.

These approaches can be applied for a complex profile of nonlinear distributions. However, it is necessary for us to predetermine a specific ideal distribution. It may be difficult to define it in some cases, especially in the early stage of product development. Moreover, the ideal distribution shall be practically realized, however, the all feasible distribution profile are not realized in the design space. Furthermore, it cannot be determined in advance that which profile is close to the ideal one in feasible distributions. Since, we design individual local thickness on the base material from a microscopic point of view with these approaches, it make us difficult to understand the film thickness distribution from the macroscopic point of view. In this situation, we are in difficult situation to obtain a technical knowledge for adjusting the manufacturing conditions so that line operators can make instantaneous judgment against problems related distribution profile.

Takahashi (2014) and Takahashi (2015) introduce depiction variables for system description to optimize an input-output like system. Using depiction variables, we can regard a distribution profile as an input-output relation. Although this approach makes us possible to design parameters for the spatial distribution profile, the challenge is how we can apply it to the practice case. Also the advantage over the conventional method should be clarified.

2. Method

As the beginning of the study, a one-dimensional distribution that can be approximated by a quadratic curve is assumed as the film thickness distribution profile for simplification. Specifically, a problem to solve in this study is the parameter optimization design for a distribution profile of plated film thickness on the plate-shaped base material into a desired profile.

In the approach proposed in this study, we depict the film thickness distribution with position on the base material as a depict variable (Mitsui (2016)). Using the statistical modeling approach, a film thickness distribution can be expressed with a statistical model as a non-linear regression equation obtained from the experimental data. The regression parameters of the statistical model are optimized with a multi-objective design. Note that the each regression parameters are associated with the feature quantities of the distribution profile. Let us denote the position on the base material as depicted variables as $\boldsymbol{m}$, and the film thickness at that position $\boldsymbol{m}$ as $\boldsymbol{y}$ ($\boldsymbol{m}$), the following quadratic regression equation from experimental data is obtained.

$$\hat{y}\ (m) = b_0 + b_1 m + b_2 m^2$$

Where both b_0 and b_1 has implemented by a centralized transformation. By the transformation, the origin of the coordinates is set to the center of the base material so that the intercept and the slope of the profile represent the centralized intercept and the tangent at the center of the base material, respectively.

Three of regression parameters, $\boldsymbol{b_0}$, $\boldsymbol{b_1}$, $\boldsymbol{b_2}$ are feature quantities for the distribution profile of the film thickness. Then, $\boldsymbol{b_0}$, $\boldsymbol{b_1}$, $\boldsymbol{b_2}$ correspond to the film thickness at the center of the base material, the eccentricity of distribution, that is deviation from the center, and the unevenness of the distribution, that is uniformity, respectively. An example of the optimization will be given below. We need to set the following constraints for the regression parameters.

$$\boldsymbol{b_0} = \mathbf{t}_{max}, \quad \boldsymbol{b_1} = \mathbf{0},\ \boldsymbol{b_2} < \mathbf{0}$$

By solving these constraints, we can get design factors to achieve the distribution profile of film thickness that has maximum film thickness as $\mathbf{t}_{max}$ at the center and it is symmetrical and convex.

2.1. Problem solving method

Principle of common electroplating process is shown in Figure 1. An electric field is generated using a direct current power source between the base material to be plated as a cathode and the anode metal set in the plating tank. In the electric field, a plating film is formed by reducing the chemical reaction of metal ions dissolved in the plating solution that occurs between the two electrodes. Electrical potential distribution of the surface of the base material is

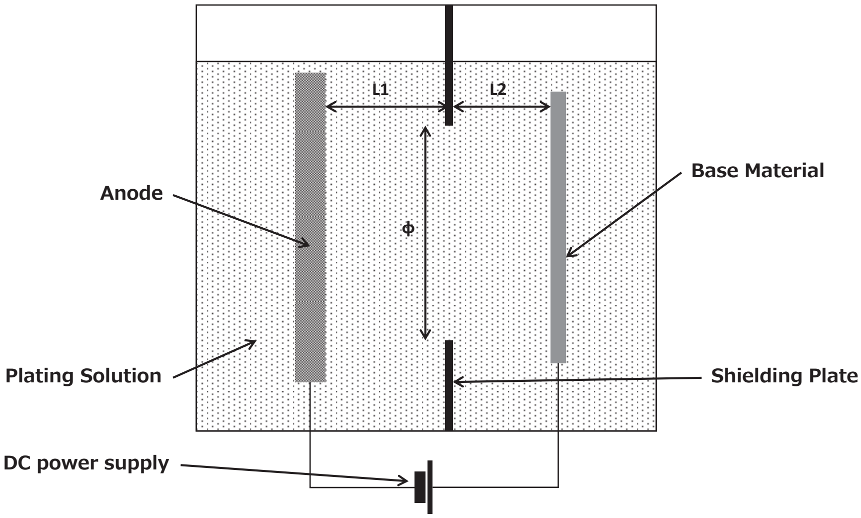

Figure 1　Principle of common electroplating process

influenced by the unevenness of the surface as well as the shape of the plating tank, polarization behavior and concentration of the plating solution. Therefore, various techniques for controlling the plating thickness have been developed. Installing a shielding plate shown in Figure 1 is one of them.

The distribution profile of the plating film becomes flat by installing a shield plate reasonably since the concentration of current can be reduced with it. In addition, the desired profile can be achieved by controlling the geometry of the shielding plate such as the distance to the cathode L1 and L2 as well as the diameter ϕ of the aperture, and so on. For example, when changing the distance L2 between the shielding plate and the plated base material to be plated, it is possible for us to control the unevenness of the profile of the plating film. In this situation, the distribution profile can be approximated to a one-dimensional quadratic curve. It is possible to control the feature quantities of the distribution profile such as position of the maximum point and the unevenness.

According to the intended use of the part in this case study, specification for the thickness at the periphery area is not severe, although the thickness of base metal center is required to be controlled to a precise value as 800 μ m to achieve the desired modification characteristics by the plating film. However, based on a demand on product function, the center of the film thickness distribution is necessary to locate at the center of the base material. In addition, the thickness of the edge area that is not important from the product function is better to as thin as possible to lead cost reduction of plating material. Therefore, the profile should be preferably formed in a convex profile. From the above discussion, the problem to be solved is summarized as the following constraints.

Request from product function

1. The film thickness at the center of the base material is 800μm.
2. The center of distribution profile will be located at the center of the base material.

Request from the cost

3. The thickness of the edge area should be thinner.

Constraint 1 is a requirement for product function to achieve the original purpose of plating on the base material and it is the most important. Constraint 2 is also a requirement from the mechanical constraints for the part environment within the product. While satisfying these two requirements, constraint 3 is required to perform further reduction of the production cost. Since the thickness of the plating film at the edge area is not important for function of the parts, it can be thinner. Cost reduction can be expected due to the reduction of plating material.

2.2. Explained case and problem setting

Based on the knowledge of the specific technology about the plating process, four design factors, X1, X2, X3, X4 have been choose as design parameters to determine the geometry related to the shielding plate. Experiments using L16 is carried out. A range of one-dimensional position on the base material is defined as M1 to M7 that is important to perfume the function of the parts, where M1 as the left end, M4 as the center and M7 as the right end of the base material. Film thickness is measured using an optical measurement tool at the in-plane seven locations of base materials.

3. Results

The statistical modeling and parameter optimization design of the acquired data is carried out using JMP®12 (SAS Institute Inc., Cary, NC, USA) along with an add-in for parameter optimization.

3.1. Optimization by the conventional approach

First, we attempt parameter optimization by applying the approach that is often used conventionally. For that purpose, we define the film thickness at the center as M4, the minimum thickness as Min, and the difference between M1 and M7 as Bias as shown in Figure 2. These three summary statistics as indices of distribution profile are calculated from the data obtained as the film thickness at the in-plane 7 points. Based on the technical knowledge that the distribution profile is symmetrical, we regard the difference between the film thickness at the right end and the left end as eccentricity of the distribution. Since it corresponds to the deviation from the center, it is named as Bias.

In this approach, data set of the film thickness at each position is described with the three summary statistics, the desired profile is obtained by the multi-objective optimization of these values by solving under the following design conditions.

Scenario 1

The optimal design is carried out under the following constraints.

Design conditions: M4 = 800, Bias = 0, Min → minimum

A unit of each value is μm but it will be omitted in the following discussion for clarity. An optimal solution and the estimated values of characteristics obtained in this condition are as

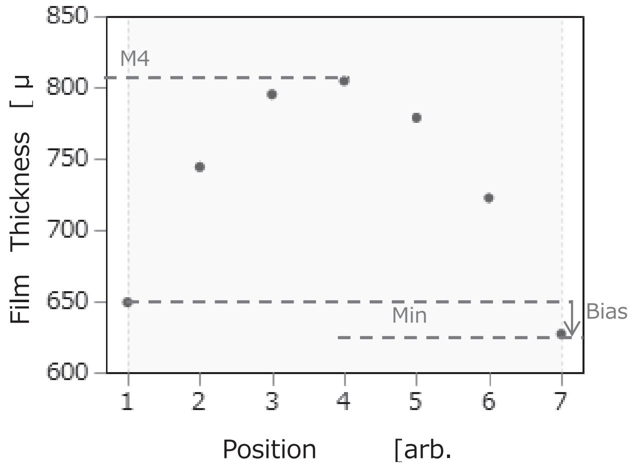

Figure 2　Three summary statistics

follows.

Optimal solution: X1 = 200, X2 = 11.0, X3 = 53.5, X4 = 195

Estimated value: M4 = 827, Bias = 0, Min = 672

Scenario 2

In the solution of scenario 1, the film thickness at the center is higher than 800. The constraints for Bias will be loosed to implement another optimization in this scenario.

Design conditions: M4 = 800, Bias → 0, Min → minimum

Optimal solution: X1 = 300, X2 = 10.9, X3 = 60.2, X4 = 142.5

Estimated value: M4 = 800, Bias = −6.62, Min = 647

Although this solution meets the specification for the thickness at the center of the base material, distribution profile is not centralized because Bias is not 0. In other words, it can be seen that there is a trade-off relationship between M4 = 800 and Bias = 0 in the constraints. In addition, it can be understood that we are in the situation that preference solutions are determined by putting the priority on function (M4, Bias) or the cost (Min).

3.2. Optimization by proposed approach

In the approach proposed in this study, the distribution profile of film thickness on the base material is designed directly from feature quantities in the regression model. Each of the coefficients of the quadratic regression model $y = b_0 + b_1x + b_2x^2$ is referred as the following, b_0 : centering sections, b_1 : slope (eccentricity), b_2 : quadratic terms, to implement the multi-objective optimization of these three distribution feature.

Scenario 1

In order to achieve the following distribution profile, the center of the distribution should be at the center of the base material and film thickness at the center M4 should be 800μm, also the thickness of the edge area should be as thin as possible, following condition might be set as the design condition.

Design conditions: $b_0 = 800$, $b_1 = 0$, b_2 → minimum

Estimated values of the distribution feature quantities with this condition are shown below.

Estimated values: $b_0 = 755$, $b_1 = 0$, $b_2 = -22.5$

In addition to the above, the position of vertex mv also can be easily estimated as the x coordinate of the vertex of the quadratic function with this approach. In this scenario, certainly mv is 4.0 corresponding to $b_1 = 0$. It can be understood that the center of the distribution is estimated to be at the base material center. The center of the distribution profile locate at the center of the base material to meet the requirement of product function, however, film thickness at the center does not meet with it.

Scenario 2

Therefore, in the next scenario, the constraints on b_1 is loosed as shown below. And the following is the estimated value in this condition.

Design conditions: $\boldsymbol{b_0} = 800$, $\boldsymbol{b_1}$ → 0, $\boldsymbol{b_2}$ → minimum

Estimate values: $\boldsymbol{b_0} = 800$, $\boldsymbol{b_1} = 5.21$, $\boldsymbol{b_2} = -14.8$, $m_v = 3.82$

Again, a trade-off relationship between the constraints $\boldsymbol{b_0} = 800$ and $\boldsymbol{b_1} = 0$ exists. This situation is the same as the situation in the conventional approach discussed in the above.

Scenario 3

With the approach proposed in this study, optimization assuming this trade-off is possible with giving ranges on where the center of the distribution should be located. Based on the request on the parts function, vertex position of distribution mv can be located within the range from 3.9 to 4.1. Therefore, the optimization design to be implemented in the following design conditions. And the estimated values of the feature quantities are as follows. This solution satisfies the desired request.

Design conditions: $b_0 = 800$, b_2 → min, $3.9 < m_v < 4.1$

Estimate values: $b_0 = 800$, $b_1 = -1.95$, $b_2 = -14.5$, $m_v = 3.93$

4. Discussion

4.1. Comparison of both approaches

The results of optimal design with both approaches are shown in Table 1 in side-by-side. Even in the approach of using summary statistics, there are two types of solution depending on priority due to the trade-off relationship in the optimal solution. Since obtained estimates with the both approaches are similar and the optimal solutions are also the nearly same except X4, it appears to be no significant difference in both approaches. However, in situations like the present case studies where the desired solution cannot be found by the conventional approach with the summary statistics, it is difficult to obtain an evaluation criterion for how much should loosen the constraint. On the other hand, the proposed approach with profile feature quantities,

Table 1　Comparison the optimized solutions delivered by the two

	Conventional approach	Proposed approach
X1	300	300
X2	10.9	11.0
X3	60.2	52.8
X4	142.5	195.0
Thickness at the center	800	800
Distribution offset	-6.62 (Bias)	-1.95 (Slope)
Thickness at the edge	647	664
Peak position	N/A	3.93

correspondence between the design space and the distribution profile is easy to grasp in order to design a distribution profile directly. Technical outlook for the adjustment of the production conditions can be easily established.

4.2. Application for the proposed approach

Capability to design a distribution profile directly is one of the advantage of the proposed method. In order to see the relationship between the design space and the distribution profile, the coefficients of the regression equation are calculated at approximately 13000 points in the design space. The appearance frequencies of three distribution feature quantities are shown in the histogram of Figure 3. According to this figure, it is clear that there is a bias in the distribution profiles obtained in this experimental space. For example, the film thickness at the center is most often about 1000 μ m, and the profile with a slope = 0 is less as frequency, that is, the profile of the distribution center is located at the base material center infrequently. Many of the profile are eccentric to the left.

The scatter diagram showing a correlation between these feature quantities are shown in Figure 4. It is turned out that there is a relatively high correlation between b_0 and b_1 This is the cause of the trade-off relation for the distribution profile control. In this figure, the result of classifying the feature quantities of the distribution profile into 20 clusters is shown by a different color. Also, the same data is expressed in two dimensional scatter plots by each cluster in Figure 5. In this Figure, b_2 is taken on the vertical axis and b_1. is taken on the horizontal axis with b_0 by shading. The asterisk in each cluster indicated the average profile of the distribution. The optimal solution at the scenario 3 lies in the vicinity of the average profile of the cluster 5.

Since proposed approach is based on the idea of designing a distribution profile directly, it is possible to rough profile control using the statistical model of feature quantities. For example, an application for performing profile control of the cluster 5 of the optimum profile group and the cluster 4 of the near profile group is shown in Figure 6.

In this case study, the geometry of the shielding plate of X1 and X2 are difficult to change, it attempts to control the distribution shape with X3 and X4. Although in the situation of Figure 6,

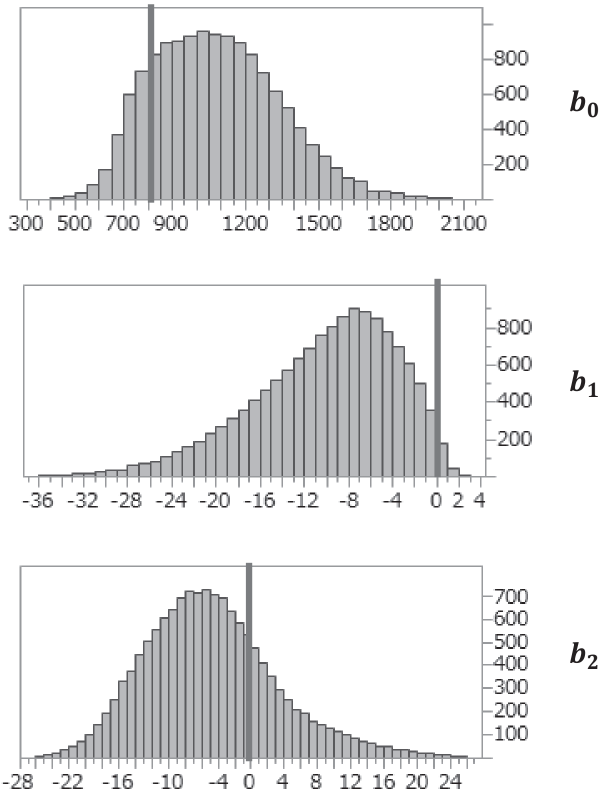

Figure 3 Histogram of the distribution profile quantities, $\boldsymbol{b}_0$, $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ (in order from the top)

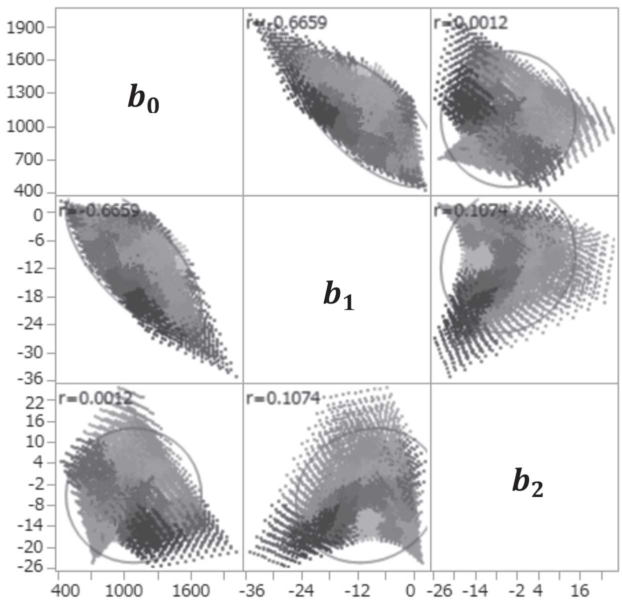

Figure 4 Scatter plot between the feature quantities

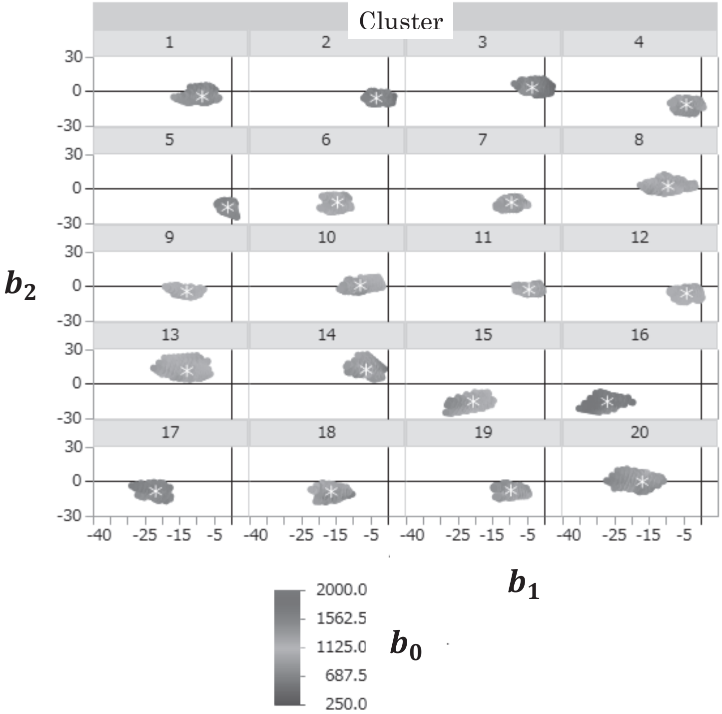

Figure 5　Classifying distribution profiles by clustering analysis

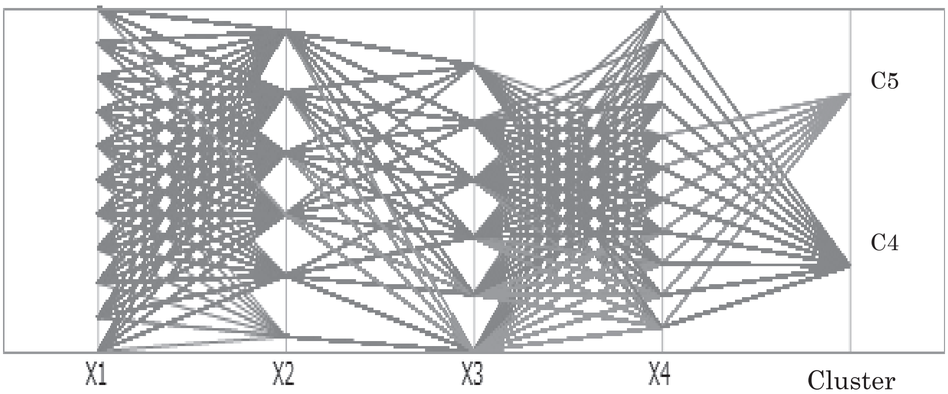

Figure 6　Parallel plot for Cluster 4 and Cluster 5

where all design factors vary almost freely, it is difficult to separate the two profile categories, rough separation is possible by control X3 only with fixing X1 and X2 to the optimum condition. As shown in Figure 7, to limit the variable range of the X3 at the lower (upper) end the profile tends to be in a category 5 (4). Using this behavior, it is easy to control the profile of film thickness distribution instantaneously by the operator's discretion at the production line.

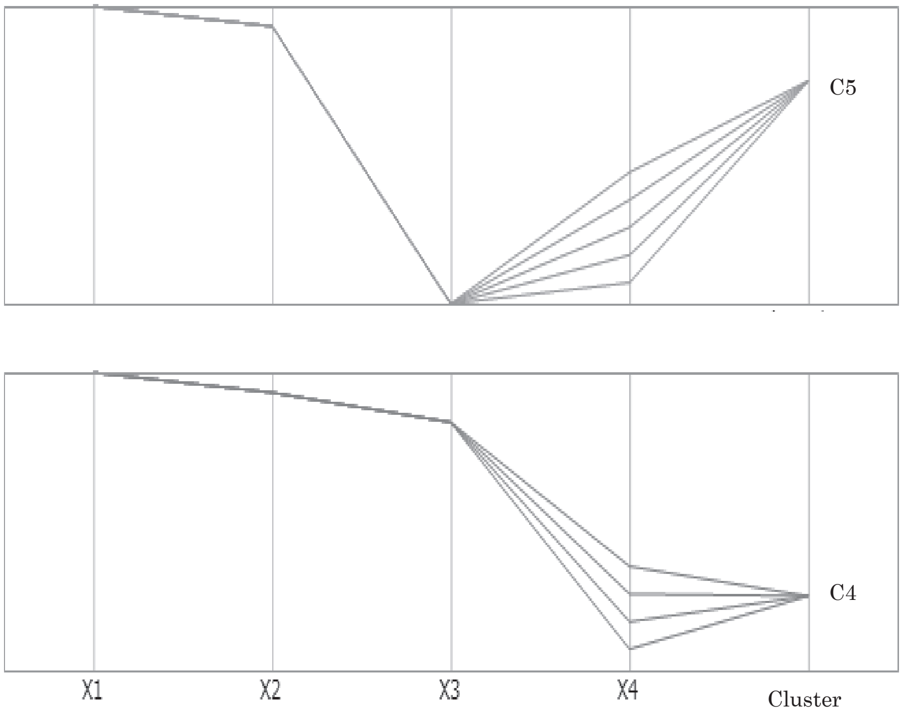

Figure 7 Separation of distribution profiles between Cluster 4 and Cluster 5

5. Conclusion

In this study, a parameter design approach for controlling the film thickness distribution into a custom profile is proposed. The regression model parameters are regarded as feature quantities of the distribution profile in this approach. It has been shown to be possible to control the spatial distribution of film thickness for engineers with higher prospect and flexibility. In this study, optimization for a one-dimensional distribution profile of the electroplating film thickness that can be approximated by a quadratic function is discussed. However, it is easy to extend this discussion to two or more dimensions. In addition, expansion of the third-order polynomial models for the distribution is not difficult. On the other hand, it is a future challenge to be applied to non-linear function system that cannot be approximated by a quadratic function, such as a four or higher-order polynomial and non-linear function.

We also point out the fact that the optimization performed in this study is just a local optimization, as we controled the distribution profile only. It is clear that we must aim to total optimization under consideration about multiplicity of systems. From this point of view, not only a distribution profile of the parts but the product the parts are used for have to be optimized together as a system with the multi-layer structure (Mitsui (2016)). In the future, we will continue to improve this approach in view of the above.

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