ISSN 1996-3343

# Asian Journal of Applied Sciences

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Asian Journal of Applied Sciences 6 (1): 16-28, 2013
ISSN 1996-3343 / DOI: 10.3923/ajaps.2013.16.28


# Analyzing the Influence of Process Parameters on Anode Usage in Electroplating Process

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## ABSTRACT
Electroplating is a process of depositing a layer of metal onto another base metal using the electrodeposition technique, where an acid is used as a medium of transferring the desired metal onto the base metal. During electroplating anodes are wasted and burnt and ended up not being used on the end product. A series of experiments with various input parameters were carried out in order to identify the best possible setting and to minimize anode usage. It was observed that for different voltage setting and electrolyte concentration the consumption of anode was more when porosity in anode basket was higher. The statistical analysis revealed that the input variables like the porosity, concentration of electrolyte and applied voltage have pronounced effect on the anode usage; however, the most significant influence was from porosity. The usage of the anodes was much less as the porosity due to the arrangement of anode in anode basket decreased. The interactive affects of the input variables such as the porosity and the voltage and the porosity and the concentration were also prominent. The second order model developed by using response surface methodology also revealed the same trend. The optimum operating conditions were identified by response optimizer plot and were verified experimentally. Both the analytical and experimental results indicated that anode usage could be reduced by 6.12% from that of the current practice. Hence by optimizing the process variables in electroplating industry, it is possible to reduce the usage significantly and to make the process cost effective.

**Key words:** Electroplating, anode, cathode, anode wastage, porosity, electrolyte concentration

## INTRODUCTION
When a product is being electroplated, a solid phase layer will be deposited on the metal surface of the product through electrical currents from an acidic solution by a process called electrodeposition. The current is transferred inside the electrolyte solution where the current will enter and leave the electrolyte by flowing through two conducting electrodes which are known as anode and cathode as mentioned by Tan (1993). Electroplating is considered as an important process in the electronic industry. It not only improves the performance but also enhances the appearance of the product. The deposition of a protective layer on the product enhances the reliability and increases the life span of the products overtime. The protective layer also imparts corrosion resistance and reduces wear in the products as discussed by Harper (2005) and Meltzer (1990).

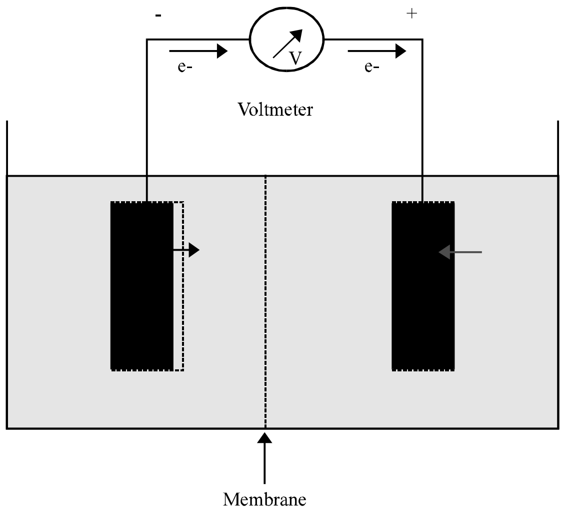


Fig. 1: Schematic diagram of electrochemical reaction in electroplating process

During electroplating process the positive ions moves towards the negative end of the voltage gradient and the negative ions will move towards the positive end of the voltage gradient. Figure 1 shows an electroplating process, where the anode and cathode electrodes are immersed in an electrolyte. The electrolyte contains the cations of the metal to be electrodeposited as described by Chung (2010) and Chung *et al.* (1999).

Tin is one of the most common anodic materials in the electroplating industry. The anodes can be of various size and shape. The anode shape and the correct placement of them inside the anode basket are crucial to obtain a uniform current flow. It can also be insoluble and soluble types. The soluble anodes are the anodes which are in the solid metal form and are placed in the electrolyte. These anodes need to be replenished as the electroplating process is carried out. The insoluble anodes or the inert anodes are made from alloys or from precious metals. They are used to maintain constant concentration in the plating bath as presented by Bach (2004). Anodes are placed in the plating cell using the anode baskets which are immersed in the electrolyte during the electroplating process. In addition, the anode also carries the current from the top of the anode basket to the bottom of the anode basket and when there is a non uniform current flow from the top to the bottom, the removal rate will be different and it was observed by Jordan (1995) and Yin *et al.* (2004). As a result, smooth and even deposition will not occur on the surface to be plated and the coating can have white spongy to spongy black appearance which is not acceptable as mentioned by Jordan (1995).

Due to the escalation of material price metal, especially tin which has increased globally nearly four folds since the last five years and it indirectly affects the cost of electroplating. In today's modern manufacturing times, cost cutting is one of the main focuses in most of the industries. The industries have employed various cost cutting measures in order to bring down the cost of manufacturing. Among the activities are just in time manufacturing (JIT), Kaizen and TQM. The main focus of all these activities is the waste elimination during processing as observed by Holman (2003). It has been studied by Grandeza and Bancud (2001) that the loss of tin anode is related to the oxidation and also due to the drag out of the electroplating electrolyte. By increasing the anode quantity in the anode basket, significant reduction of use of tin (around 44%) is possible.

Kobayashi and Mochizuki (2006) investigated that a new high-performance magnesium based anode would be able to give a higher anode current efficiency. This new design was able to prolong the life of the anode and this lead to cost reduction in the long run. Eggett and Naden (1975) have studied solvent extraction (SX) techniques in copper recovery flow sheets where it was possible to produce extremely pure copper from electrolytes by electrowinning. This study incorporated how the cost of anodes can be reduced by using lower cost lead anode instead of using higher cost non-lead anodes. Response surface methodology was applied as reported by Morris *et al.* (1997) in the separation of ranitidine and related products by capillary electrophoresis. By adopting central composite design it was observed that there was one main input factor that was significant and the optimized value of the range for the input factor was also suggested by Hanrahan and Gomez (2010).

However, there is no systematic study on electroplating process variables and how the process variables affect the consumption of anode. In this research, three main process variables, that is the porosity in anode basket, concentration of electrolytes and the supply voltage/currents were considered. The variables were varied at different levels, within the operating range of the equipment. Two level full function design was adopted to analyze and to find the main and interactive effects of process variables on anode usage. Response surface methodology was used to formulate the second order model and to optimize the processing conditions. The optimized condition was verified by experimental run. It was possible to reduce the anode usage by 6.12%. Thus the findings would provide a guideline to reduce the cost of electroplating industry and improve performance.

## FACTORIAL DESIGN AND RESPONSE SURFACE METHODOLOGY

An experimental design technique was adopted to carry out the experiments so that the results could be analyzed by the standard method. Two-level factorial design is a very simple and easy way to identify the main effects and interaction on the response of the process as investigated by Poroch-Seritan *et al.* (2010) and Montgomery (2012). This is also referred as $2^k$ factorial design with two levels for each factor with the levels known as high level and low level.

Response Surface Methodology (RSM) has been in use in the manufacturing industry as far back as 1951 where Wilson and Box collaborated together to solve an issue determining the optimum operating conditions for a particular process at a chemical company. This is also known as a meta model based optimization method as it uses linear and quadratic model approximation (Handerson and Nelson, 2006). The method can be used for mapping a response over a particular region of interest or to optimize the process variables or to meet the customer's specifications (Myers *et al.*, 2008). The results can be presented by histograms plots, scatter plots and three dimensional plots which are used for the analysis of the response surface in order to determine the interactive effects, main effects and the quadratic effects (Poroch-Seritan *et al.*, 2010).

**Use of minitab:** In order to predict the outcome of the experiments Minitab was used. A full factorial design was created in order to study and understand the effect of each of the input factors on the output variable and also to study the interactive effects of the input factors on the response. The schematic diagram of two level full factorial design is presented in Fig. 2 (Montgomery, 2012).

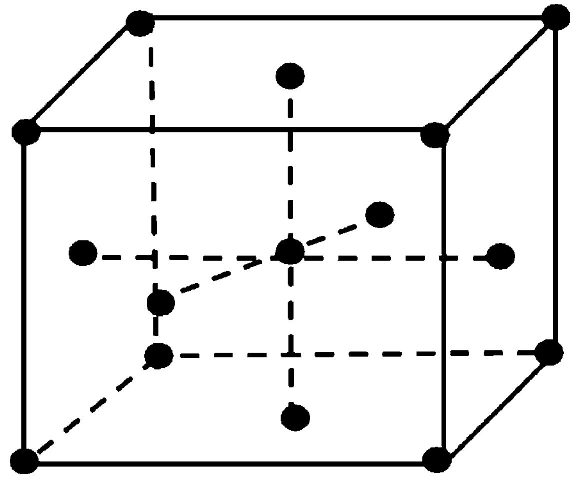

Fig. 2: Full factorial design to conduct experiment

## EXPERIMENTAL PROCEDURE

In electroplating process the wastage of anodic material is influenced by the porosity within anodic basket, concentration of the electrolyte and applied voltage. To observe the influence of the mentioned parameters, the variables were changed at various levels. The concentration of the electrolyte was varied at different levels by dilution of the chemical and topping up. The overall current flow was controlled by reducing the porosity of the anodes packed in the basket. The applied voltage was varied within the operating limit.

**Anode shapes:** Several prototypes shapes were designed and fabricated, from where two newly designed shapes with the standard shape were considered. The standard shape is of polygonal and the spherical and the cylindrical are the new shapes. These two were chosen after consideration of the machining cost which played a pivotal role in the selection. The shape of the anode is also crucial in controlling anode wastage for electroplating as the porosity within the baskets is affected by anode shape. The porosity level is obtained by first calculating the anodes volume for each shape respectively and the anode basket volume. The total number of anodes which can be placed into an anode basket is done manually by counting the average anodes out of ten baskets. The volume of each anode was multiplied by the average number of anodes per basket and the total volume was subtracted from the basket volume which was used to determine the porosity.

Hence:

$$\text{The porosity} = (\text{Total basket volume})-(\text{Volume of a specific shaped anode}\times\text{No. of anodes per basket})$$

**The concentration:** In electro deposition process, there is a minimum and maximum level of permissible concentration. Beyond the level, the plating will not be smooth and defects will be generated. Hence, within limit, minimum, maximum and central points were selected.

**The voltage setting:** The voltage setting was selected at the low point, midpoint and at the high point which was within the range of voltage setting. The voltage can be controlled by adjusting the voltage controller. By using too low of a voltage setting would disrupt the flow of the electrons and by using too high of a voltage setting would result in burnt deposits as observed by Kanani (2004).

## RESULTS AND DISCUSSION

The porosity is the space between the anodes when the anodes are filled up inside of the anode basket. The volume of different anode shapes and anode basket are presented in Table 1 which was used to calculate porosity.

**Calculation of the porosity:** The porosity for each specific shape was calculated from volume of the shape and the volume of the basket holding the shapes. The volume of each shape is presented in Table 1. The lowest porosity was obtained with Shape 1.

$$\text{Shape 1} = \text{B cm}^3\text{-(No. of anodes}\times\text{S cm}^3) = X_1\ \text{cm}^3$$

$$\text{Shape 2} = \text{B cm}^3\text{-(No. of anodes}\times\text{P cm}^3) = X_2\ \text{cm}^3$$

$$\text{Shape 3} = \text{B cm}^3\text{-(No. of anodes}\times\text{R cm}^3) = X_3\ \text{cm}^3$$

where, $X_1\ \text{cm}^3 < X_2\ \text{cm}^3 < X_3\ \text{cm}^3$.

**Results:** Experiments were conducted under different operating conditions. The usage of anode with porosity at various electrolyte concentrations for different voltage settings is presented in Fig. 3-5.

It is observed from Fig. 3 that at low voltage setting, the anode wastage is more at higher porosity level and the wastage is increased further with higher level of electrolyte concentration. The disruption of current flow due to low voltage setting and increase of resistance due to higher

Table 1: Shape and volume of anode in anode basket to calculate porosity

| Shape in code | Volume in code |
|---|---|
| Shape 1 | S $cm^3$ |
| Shape 2 | P $cm^3$ |
| Shape 3 | R $cm^3$ |
| Basket | B $cm^3$ |

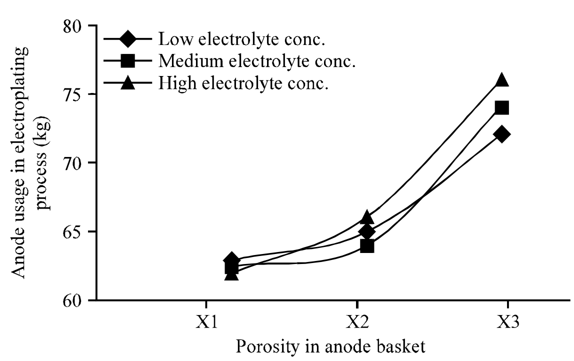


Fig. 3: Variation of anode usage with porosity and electrolyte concentration for low voltage setting

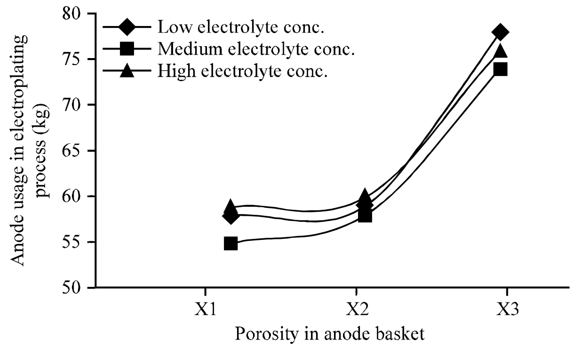


Fig. 4: Variation of Anode usage with porosity and electrolyte concentration for medium voltage setting

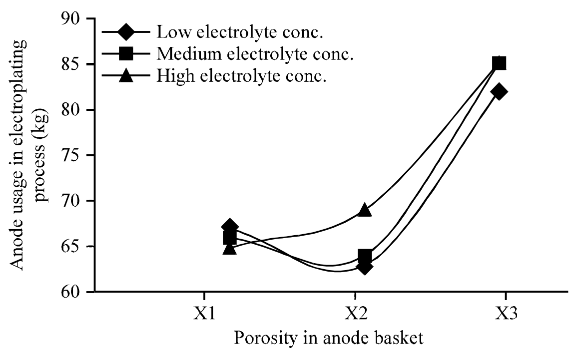


Fig. 5: Variation of anode usage with porosity and electrolyte concentration for high voltage setting

porosity have resulted more consumption of anode (Kanani, 2004). The use up of anode was higher at all concentration level of electrolyte, when porosity in anode basket is raised; however, it was more at lowest electrolyte concentration as observed in Fig. 4. The higher resistance due to porosity disrupted the current flow between anodes and low electrolyte concentration in electroplating resulted in more consumption of anodes in electroplating process. Hence, anode has decreased at a faster rate (Jordan, 1995). However, at high voltage setting as shown in Fig. 5, the trend for electrolyte concentration is different. At medium porosity the anode usage was less for low and medium electrolyte concentration. The lowest value of anode consumption was achieved at medium voltage setting with minimum porosity and medium electrolyte concentration. Under this setting the anode wastage was reduced by 5.12% from that of the standard practice in the industry. The phenomenon can be explained by the interactive effects of different parameters which are discussed below. The interactive effects are evaluated by statistical analysis.

**Statistical analysis:** For this purpose a full factorial design was first created in Minitab with the low points, middle points (median points) and high points specified for each of the three variables (porosity, concentration and voltage). Four additional runs were replicated at the center point (median). The design of experiments were used to find out main and interactive effects on the output and presented in Table 2.

It was observed from the Table 2 that all the three variables are affecting anode usage; however, the effect of the porosity is much higher than that of voltage applied and electrolyte

Table 2: Interacting effects of different variables on anode usage

| Interacting effects | Effect |
|---|---|
| Porosity | 14.75 |
| Concentration | 0.75 |
| Voltage | 6.25 |
| Porosity×concentration | 2.25 |
| Porosity×voltage | 2.75 |
| Concentration×voltage | -0.25 |

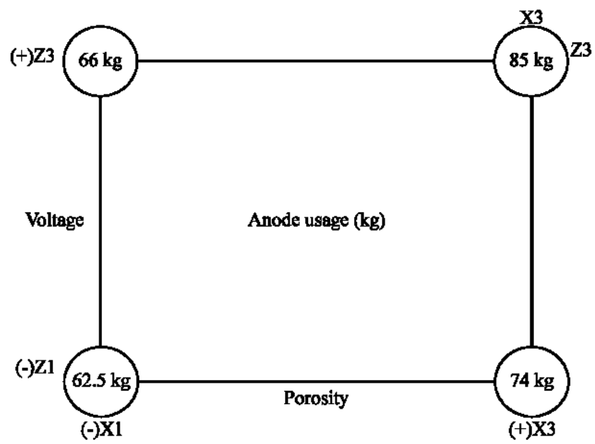


Fig. 6: Interaction of porosity and voltage on anode usage

concentration. The positive value of analysis indicates that the higher level of porosity increases the anode usage, thereby, causing more wastage of anodes. This is due to the flow of the current between the anodes which is affected when the porosity is increased. In addition to that, the interactive effects of porosity and concentration and porosity and voltage were also observed.

The interactive effect of the porosity and voltage is diagrammatically presented in Fig. 6. At lower porosity, the increase of voltage increases anode usage by 3.5 kg but at higher porosity, the change caused the increase of anode consumption by 11 kg. When both the porosity and the voltage are at maximum the anode usage is at 85 kg. As mentioned earlier as the porosity increases the packing (placement) of the anodes in the anode basket becomes loose, this in turn increases the resistance of the current and hence, the flow of current is greatly reduced. When the flow of current is reduced, the voltage is increased in order to compensate for the resistivity as investigated by Jordan (1995).

However, the higher voltage result in higher current flow which directly increases the electrolyte temperature and the plating becomes less efficient, thereby, causing the electroplating process to use more anodes as observed by Jordan (1995).

The interactive effects of porosity and concentration are diagrammatically sketched in Fig. 7. At lower level of electrolyte concentration, the increase of porosity has increased anode usage by 20 kg and at a lower level of porosity the increase of concentration has increased the anode usage by 1 kg. When both the porosity and the concentration are at maximum the anode usage is 76 kg.

This is due to the reason that when the concentration of the electrolyte is low, the anodes will decrease at a faster rate, as the amount of soluble Sn in the electrolyte will be less and the Sn from the anodes are used up more as observed by Schlingsinger and Paunovic (2000).

Table 3: Response Surface Methodology (RSM) block design and usage of Anode

| Std. order | Run order | Center Pt | Blocks | Porosity | Concentration | Voltage | Usage |
|---|---|---|---|---|---|---|---|
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 85 |
| 6 | 2 | 1 | 1 | 1 | -1 | 1 | 82 |
| 11 | 3 | 0 | 1 | 0 | 0 | -0 | 58 |
| 3 | 4 | 1 | 1 | -1 | 1 | -1 | 62 |
| 12 | 5 | 0 | 1 | 0 | 0 | -0 | 58 |
| 2 | 6 | 1 | 1 | 1 | -1 | -1 | 73 |
| 10 | 7 | 0 | 1 | 0 | 0 | -0 | 58 |
| 7 | 8 | 1 | 1 | -1 | 1 | 1 | 65 |
| 5 | 9 | 1 | 1 | -1 | -1 | 1 | 67 |
| 4 | 10 | 1 | 1 | 1 | 1 | -1 | 76 |
| 9 | 11 | 0 | 1 | 0 | 0 | -0 | 58 |
| 1 | 12 | 1 | 1 | -1 | -1 | -1 | 63 |
| 20 | 13 | 0 | 2 | 0 | 0 | -0 | 58 |
| 16 | 14 | -1 | 2 | 0 | 1.681793 | -0 | 68 |
| 18 | 15 | -1 | 2 | 0 | 0 | 1.681793 | 68 |
| 13 | 16 | -1 | 2 | -1.68179 | 0 | -0 | 55 |
| 21 | 17 | 0 | 2 | 0 | 0 | -0 | 58 |
| 15 | 18 | -1 | 2 | 0 | -1.68179 | -0 | 68 |
| 14 | 19 | -1 | 2 | 1.681793 | 0 | -0 | 79 |
| 17 | 20 | -1 | 2 | 0 | 0 | -1.68179 | 72 |
| 19 | 21 | 0 | 2 | 0 | 0 | -0 | 58 |

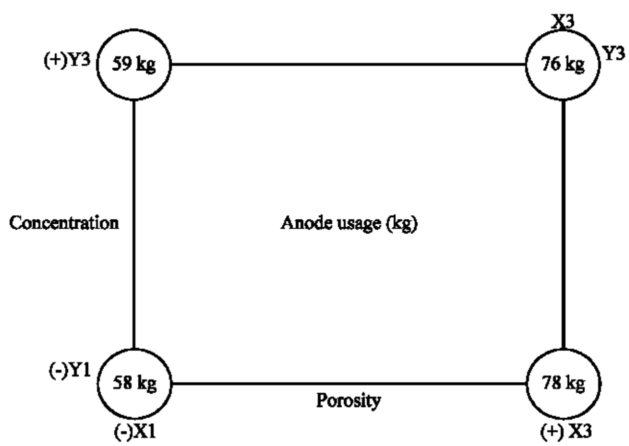


Fig. 7: Interaction of porosity and concentration on anode usage

RSM blocking design was used to optimize the run and was designed automatically by Minitab. The block design and anode usage are presented in Table 3.

From the blocking design additional input variables were generated which were lower and higher than the present minimum and maximum input variable, respectively. Automatically generated set conditions were used to conduct actual experiments. In Table 3, the value-1.68179 is a value lower than the lower point of porosity, concentration and voltage, respectively and 1.68179 is a value higher than the high of porosity, concentration and voltage, respectively. From these input variables, the output variable (usage) was determined by conducting the experiments as per the settings.

**3-dimensional surface plot for usage of anode:** The 3-dimensional (3D) surface plots can be used to give a good description on how the usage of the anodes varies with the settings of the porosity, the electrolyte concentration and the voltage setting. This can be used as a guide to obtain the optimal settings. The 3-dimensional plots of anode usage vs. concentration, porosity is given in Fig. 8.

The lowest point of anode usage is at porosity $X_1$ $cm^3$ and the concentration of the electrolyte is at approximately $Y_2$. Figure 9, shows the anode usage with respect to porosity and voltage. The lowest point of anode usage is at the porosity is approximately $X_1$ $cm^3$ and at a voltage of at $Z_{1.5}$ Volts.

Figure 10 presents the plot of anode usage with concentration and voltage. From the graph it is observed that the lowest point of anode usage is when the concentration of the electrolyte is at $Y_2$ g $L^{-1}$ and the voltage is at $Z_{1.5}$ volts.

It is clear from the plot that the porosity plays a very important role in anode usage. As explained previously when the porosity increases the flow of current is greatly reduced and the

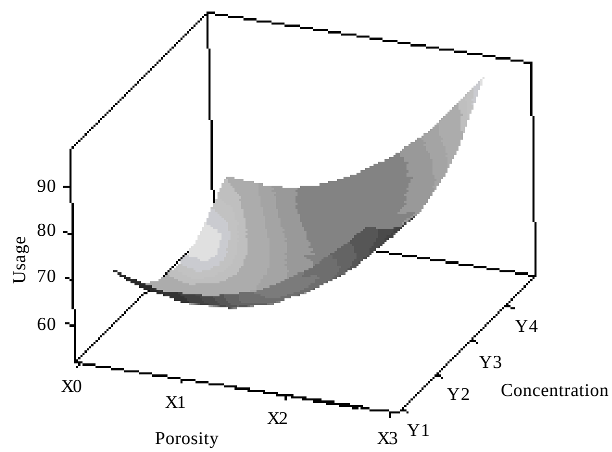


Fig. 8: Surface plot of anode usage vs. concentration, porosity

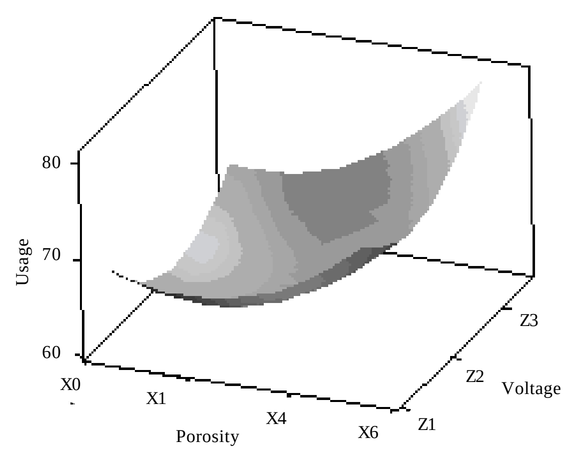


Fig. 9: Surface plot of anode usage vs. voltage, porosity

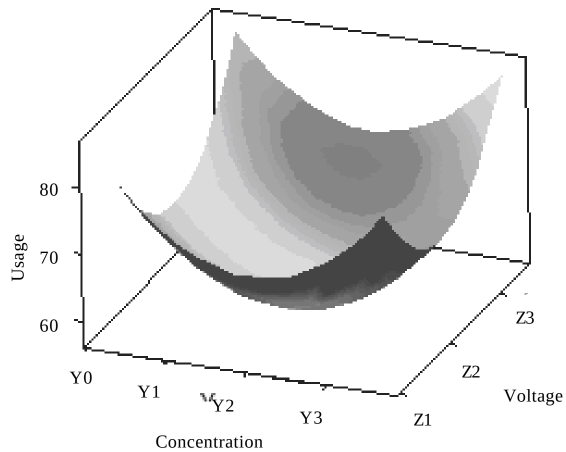


Fig. 10: Surface plot of anode usage vs. voltage, concentration

voltage is increased in order to compensate for the resistivity. As it is known that V = IR, hence, when there is a high voltage the current density of the strip increases and more anodes is consumed at a higher rate and more anodes is deposited onto the plated surface (Jordan, 1995).

**Model formulation using RSM:** The experimental data was used to develop a second order model to predict the response behavior with the process variables and the relationship obtained was as followed:

$$R = 57.9262+4.3261X+0.1306Y+0.7956Z+1.3223X^2+1.4473Y^2+1.6973Z^2 +0.3977XY+0.4861XZ-0.0442YZ$$

where, R is Anode usage.

It can be seen from the developed model that the consumption of anodes will be increased with the increase of porosity, concentration of electrolyte and applied voltage. However, the most significant factor is porosity and the interactive effects of parameters are also prominent, except the interaction of concentration and voltage.

**Analysis of the response surface design:** By using RSM the optimized values of variables were identified which are porosity -1.0023 (coded value), concentration 0.1189 and voltage 0.0170. Under this condition the usage of anode was minimum which 54.3415 kg is. The plots of optimizer are presented in Fig. 11-12.

The response optimizer was then adjusted by moving the vertical bars to see how each factor affects the response and whether it is possible to reduce the use of anode further.

The optimized values for the variables are porosity: -1.00, concentration: 0.1189 and voltage: 0.0170. Under this condition the usage of anode was minimum which 54.3414 kg which is 6.12% lower than the standard practice in the industry. In order to verify the optimizer suggested values, confirmation runs were conducted. The values of the input parameters from the response optimizer suggestion were first calculated and ten tests were conducted under the optimized conditions

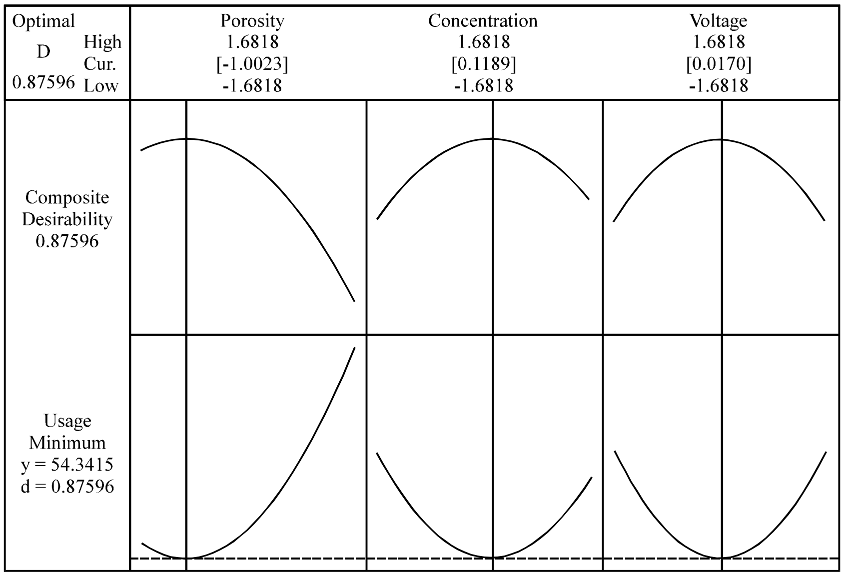


Fig. 11: Response optimizer initial plot on anode usage

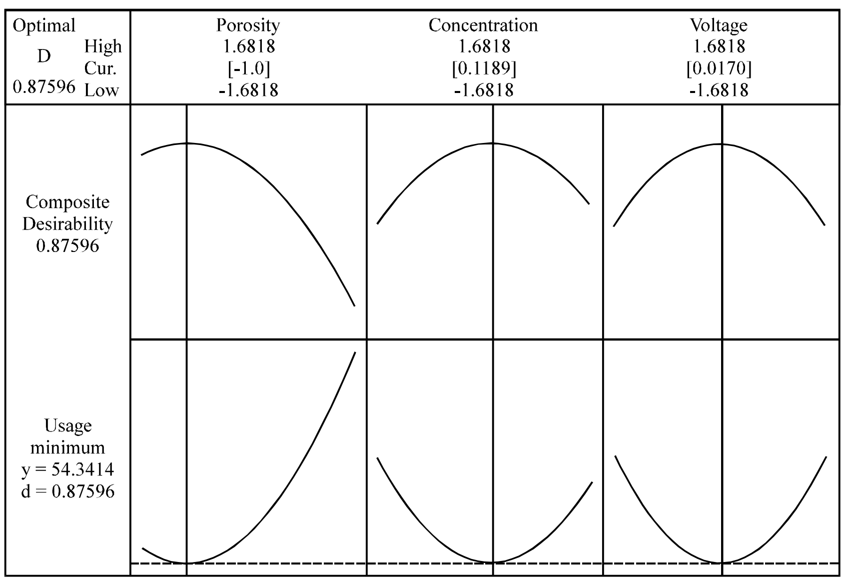


Fig. 12: Response optimizer modified plot on anode usage

identified from RSM. When the electroplating process was carried out under the optimized conditions evaluated by RSM, the average anode usage was 54.45008 kg. The predicted value of anode usage under optimized condition using RSM is 54.3414 kg. Hence the predicted and experimental values of anode usage under optimized conditions are in close agreement.

## CONCLUSION

The affect of different process variables on the usage of the anodes in the electroplating process has been analyzed. By using statistical tools the main and interacting affects of the variables are identified. The analysis of the end results obtained from all the experiments conducted showed that the usage of the anodes varied when the input variables are changed. It is also evident that the combination of two or more input variables played a greater role in reducing the anode usage. One of the main contributors for the high anode usage is the porosity in between the anodes which are packed inside the anode basket. The higher porosity causes an increase of resistance which ultimately results a higher voltage setting and ends up with more use of anodes in the electroplating process. As a result consumption of anodes is increased. Hence, the proper anode shape with the least porosity inside the anode basket is crucial to reduce anode usage. The model predicted by RSM also revealed the same truth. Not only that the optimum conditions identified by response optimizer was also verified by actual experiments. The difference of analytical value and actual run can be neglected. The identified optimum condition reduced the anode usage by 6.12% than that of the present operating conditions. Hence, it can be said that by optimizing the operating conditions in electroplating process the anode usage can be minimized and thereby making the process cost effective.

## ACKNOWLEDGMENTS

This study was carried out as a part of the research work for masters in mechanical engineering. All the research activities were conducted at Freescale Semiconductor, Malaysia Sdn. Bhd. and the authors gratefully acknowledge the materials and testing facilities provided by them.

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