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Optimizing Electroplating Process Parameter and Sn-Plating Thickness Uniformity using Modified Shielding

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ABSTRACT

Uneven plating thickness distribution across plated surface has become a major challenge in electroplating industry mainly due to the complexity of package design. In most cases, controlling the plating thickness uniformity to the specific area according to the required package design specification can be a challenging task for the manufacturer which can result in high losses. The plating thickness uniformity are closely related with the electroplating process parameter and the passage of current between anodes to cathode. To deal with the current passage, a shielding technique that control the disposed area between the anode and cathode can be an effective way. Therefore, the aim of this paper is to study the electroplating process parameters (current and speed) for improving the Sn-plating thickness uniformity using modified mechanical shielding. Taguchi method is adopted to reduce the size of experiment and optimize the process parameters simultaneously. As a result, new parameter has been established which offer ideal plating thickness with less variation and stable Cpk. From the conducted experimental work, it shows that by employing the right physical resistance shielding aperture able to selectively alter or modulate the electric fields between the anode and the plating surface on the embodiment and thereby control the electro deposition rate across the area of the plating surface.

Keywords: Electroplating, manufacturing process, physical shielding, precision engineering

1. INTRODUCTION

In the electronic packaging industries, soldering materials are essential in joining various microelectronic networks. Solders assure the reliability of joints and protect the microelectronic packaging devices. They provide electrical, thermal, and mechanical continuity among various interconnections in an electronic device. The service performance of all the electronic appliances depends on high strength and durable soldering materials. Lead-containing solders are in use for years, resulting in an extensive database for the reliability of these materials. A lead frame is utilized in the semiconductor device assembly process and is essentially a thin layer of metal that connects the wiring from tiny electrical terminals on the semiconductor surface to the large-scale circuitry on electrical devices and circuit boards. Lead frames are used in almost all semiconductor packages. Most kinds of integrated circuit packaging are made by placing the silicon chip on a lead frame, then wire bonding the chip to the metal leads of that lead frame, and then covering the chip with plastic. This simple and usually low-cost packaging is still the best solution for many applications.

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The leadframes of semiconductor devices, such as ICs, transistors and diodes, are becoming increasingly diversified and are required to be higher in precision. Uneven plating thickness distribution across plated surface has become a major challenge in electroplating industry even for advanced plating technology today due to complexity of package design. To control current distribution, many approaches have been reported, including the optimization of electrode shapes, masks, shields, and current thieves. However, these approaches can be time consuming if they are performed by trial and error. Therefore, numerical analysis helps the plating industries to design on the most appropriate configuration of deposition cells to produce the best deposit uniformity on each part.

A number of natural phenomena occur in the electroplating process has cause the material to be deposited unevenly on the leadframe. One of the factors is due to complexity of leadframe geometry design and size of targeted surface area [1]. Much effort has been devoted towards minimizing the effects of such phenomena so that an even Tin-deposition is achieved. One common approach includes placing physical barriers, called "shields", between the anodes and cathode substrate areas where the deposition concentration tends to be higher. The shields offer a high resistance path to the material ions from anodes to cathode. While the height position of shields determines the effectiveness of current distribution density. In addition, improper shielding position causes uneven plating thickness, too high at one position and too low at other position across plated material. Low plating thickness caused many reliability issues and downstream process obstacles. Common issues with the uneven plating thickness is the formation of voids that can cause thermal shock as shown in Figure 1.

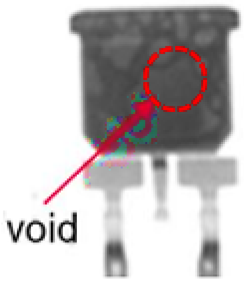


Figure 1. Void formation resulting from uneven deposited material.

In order to increase the competitiveness in cost and time, the plating thickness need to be as thin as possible (meet the target cpk requirement) with uniform thickness. However, it is difficult to optimize the plating thickness with uniform distribution because of it dependence on many factors such as leadframe design, electroplating process parameter and the passage of current between anodes to cathode. Therefore, it becomes a popular trend in the recent year to design shielding position in order to reduce the plating thickness variation.

2. SHIELDING AS PHYSICAL RESISTANCE

Various attempts have been made to improve the distribution of plating materials on a workpiece. For instance, including a shielded anode basket housing nickel chips. Other attempts to control the plating thickness of a workpiece include the provision of a pumping device to redirect the electrolytic plating solution from the bottom of a tank upward, as disclosed in [2]. This apparatus is complex and thus not well suited for use with semiconductor lead frames. Plating uniformity also can be achieved by optimizing throwing power determine uniformity of the thickness of a coating deposited on irregularly shaped part. Leveling is ability of electroplating process to deposit smooth uniform coating on the rough surface [3].

In accordance with current invention, an electroplating system capable of controlling the thickness of metal film electrodeposited onto a substrate is established. The electroplating system includes a standard electroplating apparatus and a non-conductive opening, which is disposed in the electroplating apparatus to selectively alter or modulate the electric fields between the anode and the plating surface on this embodiment and thereby control the electrodeposition rate across the area of the plating surface. The shield is disposed between the anode and the cathode. As a result, the electric field current density is applied to every point evenly as possible on the plating surface. Because the electrodeposition rate depends on part on the characteristics of the electric field, the uniformity of the thickness profile of the electrodeposited metal can be manipulated by the size of the shield and of the shield apertures [4].

A functional block diagram as physical barrier selected for this experiment is fabricated with opening at center of the shielding plate. The purpose of the opening is to allow more focus plating deposition on heatsink. While the lead is resisted by about 30% reduction of deposition. Polypropylene (PP) polymer is selected due its excellent resistance to high temperature and chemical which known to cause such cracking such as sulfuric acid mixture and concentrated hydrochloric acid/chlorine mixtures. The illustration of modified shielding as Figure 2 below without any dimensions as to protect the intellectual properties of manufacturer. The shielding is fixed on the anode basket between anode and cathode and only located at the first cell.

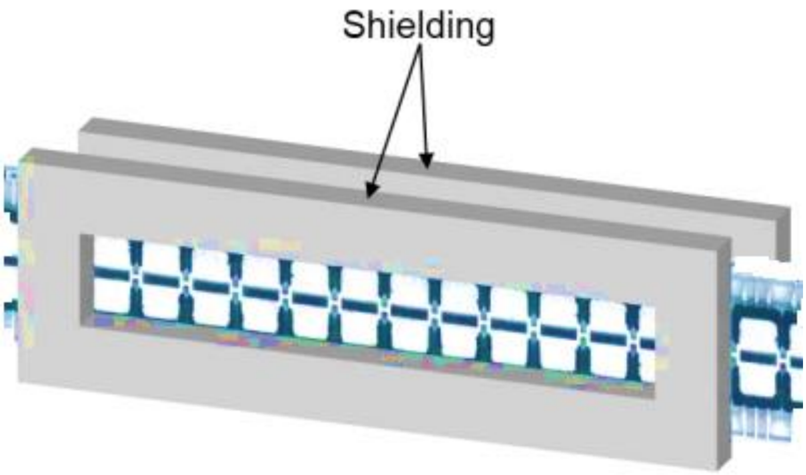


Figure 2. Shielding design.

3. MATERIAL AND METHOD

3.1 Plating Equipment

The industry standard for leadframe solder plating with an installed computer controlled Electro DeFlash/Electro PlatingLine systems is used for this research. This is continuous plating strip to strip by the carrier belt. Therefore, distribution from product to product is excellent with control variation seen in distribution from one product type to another type. In addition, the products are very close to each other loaded onto the carrier belt. The gap is only 2 or 3 mm between each product, therefore no burning is seen, similar to normal reel-to-reel processing. In addition, bottom shielding in the plating bath is controlled by the computer and is menu-driven based on the product. The shielding reduces the plating on the lower areas of the product (dog bone effect) and is fully automatic, requiring no operator adjustment.

3.2 Electrolyte: Methanesulfonic Acid (MSA) Tin

The MSA tin used is from Solderon™ ST-300T matte tin electroplating electrolyte. The Solderon™ ST-300T matte tin process enables high-throughput for maximum cost benefit while delivering exceptional performance. It offers single additive system for easy control, high current density for high throughput in production, low whisker propensity and excellent solderability at lower solder pot temperature. Table 1 depicted the detail composition of MSA tin used in the experiment.

Table 1 Properties of MSA (Solderon ST-300T)

Component	Concentration
Tin Compound	45.0% – 55.0%
Water	35.0% - 45.0%
Sulfonic acid	5.0% - 15.0%
Lead	<0.01%

3.2 Experimental Setup and Procedure

The molded cut strips of the IC part are placed in stack and fully automatically loaded onto an endless carrier belt. A specially design clip device holds the strips in mechanically and electrical contact with the metal carrier belt as shown. The continuously moving carrier belt transports the strips through pre-treatment, rinse, plating, post treatment and drying stations to the fully automatic, synchronized unload position where the strips are discharged into the magazines. In the return passage the carrier belt can be stripped to remove possible flash deposits. After the leadframe been plated, it will undergo annealing process for 1 hour in temperature of 150 °C ± 5 °C. After that, Sn-plating measurement will be performed using XRF equipment prior to solderability test, adhesion test and SEM analysis.

The experimental design to optimize the electroplating process parameter for Sn-plating leadframe is L_9 orthogonal array based on the Taguchi method with 2 parameters and 3 levels. This L_9 orthogonal array requires total 9 experiments with various combinations of parameters as shown in Table 2 and 3. The other process parameters such as duty cycle, frequency, electrolyte and addictive concentration, pH, temperature and stirring rate are kept constant and as recommended by manufacturer to maintain robustness of current process.

Table 2 Factor and Level

Process Parameter	Concentration		
	Low	Medium	High
Current (Amp)	60	90	120
Speed (m/s)	3.0	3.5	4.0

Table 3 L_9 Orthogonal Array Experimental Design

Exp. No.	Process Parameter	
	Current (Amp)	**Speed (m/s)**
1	60	3.0
2	60	3.5
3	60	4.0
4	90	3.0
5	90	3.5
6	90	4.0
7	120	3.0
8	120	3.5
9	120	4.0

4. RESULTS AND DISCUSSION

Preliminary run has been conducted using the single shielding design and position. Based on literature review, plating thickness uniformity can be achieved by using shielding as physical barrier or resistance inside the plating bath. To prove this claimed, simple evaluation with shielding and without shielding were performed. From the result, variation (Stdev) of plating thickness reduced from 1.35 to 1.05 as below. These results strongly suggest that current distribution in cells using the modified shield will be more uniform than in cell that use un-modified shield. The shields direct the flow of current into the shortest path between the anode and cathode or concentrate the flow of metal ions and direct them to a normally low current density area. On the other hand, it intercepts the flow of metal ions and force them to flow through a longer path to reach the normal high current density region of the cathode. It reduces the maximum deviation in the current distribution by about 20% as shown in Figure 3.

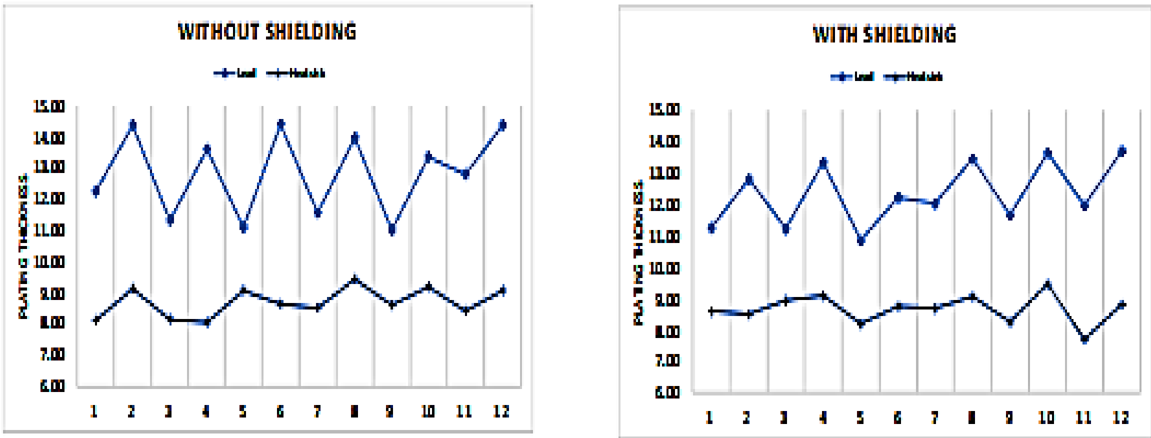


Figure 3. Plating thickness result with and without shielding.

However, the design factor consideration and other influencing parameter is not further characterized. From this single data run it shows that the uniformity of the thickness can be improved further.

4.1 Analysis of Plating Thickness Cpk

The process capability index (Cpk) calculated based on the established equations (1) below. As per product specification, the upper specification limit (USL) is 15um, while lower specification limit (LSL) is 7um for lead and heatsink. Using the following formula, the value of Cpk generated. Cpk is selected due to it combine the thickness mean and variation, and quantify it as index. Table 4 shows the results of Cpk of individual location lead at first row (Lead 1) and lead at second row (Lead 2) for all runs.

$$Cpk = \frac{\min(USL - mean, mean - LSL)}{3\sigma}$$

$$Cpk = \frac{\min(15 - mean, mean - 7)}{3\sigma}$$

Table 4 Experimental Result for Cpk

Exp. No.	Process Parameter		Responses Measured	
	Speed (m/s)	Speed (m/s)	Cpk on Lead 1	Cpk on Lead 2
1	60	3.0	1.01	0.71
2	60	3.5	1.50	1.30
3	60	4.0	1.20	1.40
4	90	3.0	1.70	1.35
5	90	3.5	1.90	1.52
6	90	4.0	1.50	1.30
7	120	3.0	1.60	1.20
8	120	3.5	1.80	1.13
9	120	4.0	1.85	1.30

Based on result, Cpk Lead1 and Lead2 response is further analyzed using Design Expert program to get optimize solutions. Cpk is selected due to it combine the thickness mean and variation, and quantify it as index.

Statistical ANOVA of Cpk Lead1 and Lead2 results (Table 5 and 6) was performed to further investigated the effects of electroplating parameters. Based on the ANOVA, a quadratic model was selected to exemplify the relationship of electroplating parameters effects towards the Cpk Lead1 which gives the lowest value of "Prob> F" of 0.1099. While for Cpk Lead2, a two-factor-interaction (2FI) with 0.0206 of "Prob>F" value is suggested to fit the model relationship [5].

Table 5 ANOVA for Cpk Lead1

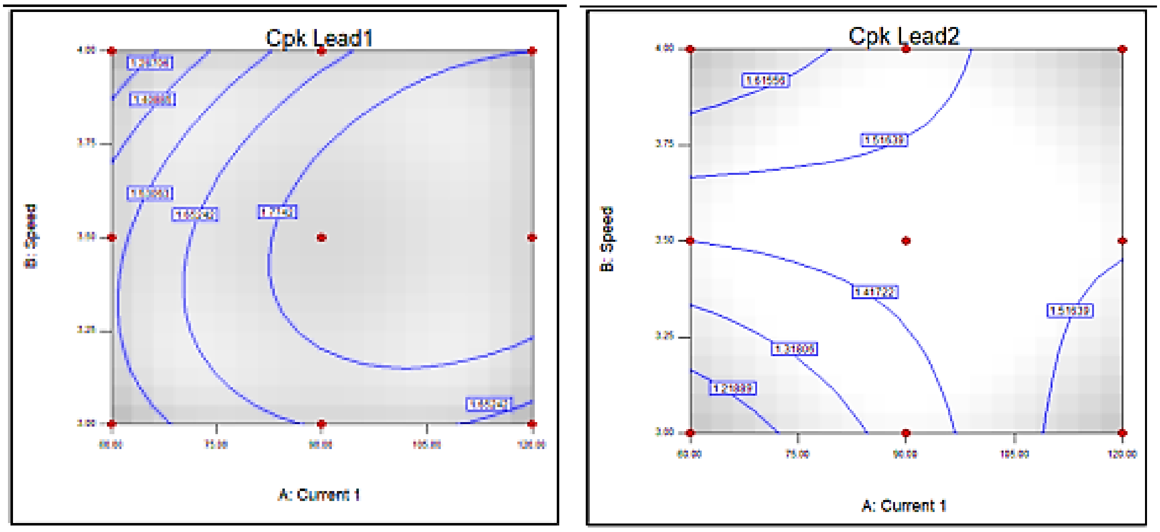
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.39	5	0.078	6.89	0.0715
A	0.22	1	0.22	19.55	0.0215
B	3.750E-003	1	3.750E-003	0.33	0.6045
A^2	0.040	1	0.040	3.56	0.1556
B^2	0.073	1	0.073	6.52	0.0837
AB	0.051	1	0.051	4.49	0.1243
Residual	0.034	3	0.011		
Cor Total	0.797911	8			

Table 6 ANOVA for Cpk Lead2

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.23	3	0.076	5.43	0.0496
A	0.012	1	0.012	0.87	0.3942
B	0.060	1	0.060	4.29	0.0932
AB	0.16	1	0.16	11.15	0.0206
Residual	0.070	5	0.014		
Cor Total	0.30	8			

From the analysis, it indicated that current is the most significant factors that affect the Cpk Lead1. The Model F-value of 6.89 implies there is a 7.15% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. While for response Cpk Lead2 in Figure 4.8, the Model F-value of 5.43 implies the model is significant. There is only a 4.96% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant [6]. In this case AB are significant model terms.

The results revealed that, the plating thickness Cpk on lead 1 improving when increase of current and speed based on model prediction contour in Figure 4(a). This setting control plating thickness on lead 1 so that thickness variation reduced. Thus, more uniform thickness on overall lead. Further, the plating thickness Cpk on lead2 improving at low current but high belt speed based on model prediction contour in Figure 4(b). This setting reduces the plating thickness on lead 2, which tend to plate thicker. Thus, more uniform thickness on overall lead.



(a) Plating thickness Cpk Lead 1

(b) Plating thickness Cpk Lead 2

Figure 4. Contour graph for Cpk Lead1 andLead2.

From the ANOVA analysis, mathematical equations model generated for each responses Cpk Lead1 and Cpk Lead2. This model will be used for the prediction of optimized model. The final equation as below:

$$\text{Cpk Lead1} = -6.87639 + (8.4722\text{E-}003 * \text{Current}) + (4.64167 * \text{Speed}) - (1.57407\text{E-}004 * \text{Current2}) - (0.76667 * \text{Speed2}) + (7.50000\text{E-}003 * \text{Current} * \text{Speed})$$

$$\text{Cpk Lead 2} = -3.52028 + (0.047583 * \text{Current}) + (1.38500 * \text{Speed}) - (0.013167 * \text{Current} * \text{Speed})$$

4.2 Parameters Optimization

Table 7 shows the optimization parameter based on Cpk obtained from Taguchi's planned experiment. For optimization current and speed, are set in range meanwhile the respond, which is Cpk set to be maximize. The results indicate the optimal combination of parameters associated with good Cpk of plating thickness in electroplating IC package and optimal combination parameters are using current density 120 Amp and belt speed 3.46 m/min. These combination parameters give values of Cpk on 1.87 and 1.51 respectively on lead1 and lead2.

According to model above, the desirability to achieve good Cpk is 0.746. In other word, the percentage for the experiment to be succeeded using these combination values parameters is 7.46%. Breakdown of parameter and response are shown in Figure 4 and 5. The experimental results recommended the electroplating process parameters assisted by modified mechanical shielding would be optimized the Cpk based on Taguchi method, by using the appropriate parameters as concluded in the Table 6. This parameter is validated using qualification run of three lots.

Table 7 Constrain and Parameter Optimisation Result

Constraint						
Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
Current	in range	60	120	1	1	3
Speed	in range	3	4	1	1	3
Cpk Lead1	maximize	1.2	1.9	1	1	3
Cpk Lead2	maximize	1.16	1.76	1	1	3
Solution						
Number	**Current**	**Speed**	**Cpk Lead1**	**Cpk Lead2**	**Desirability**	
1	120	3.46	1.86966	1.51493	0.746	Selected

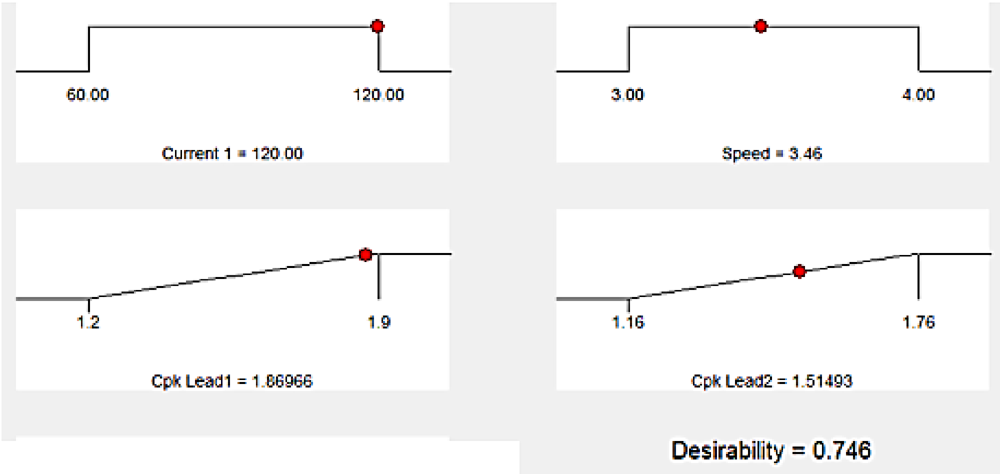


Figure 5. Desirability of optimization result.

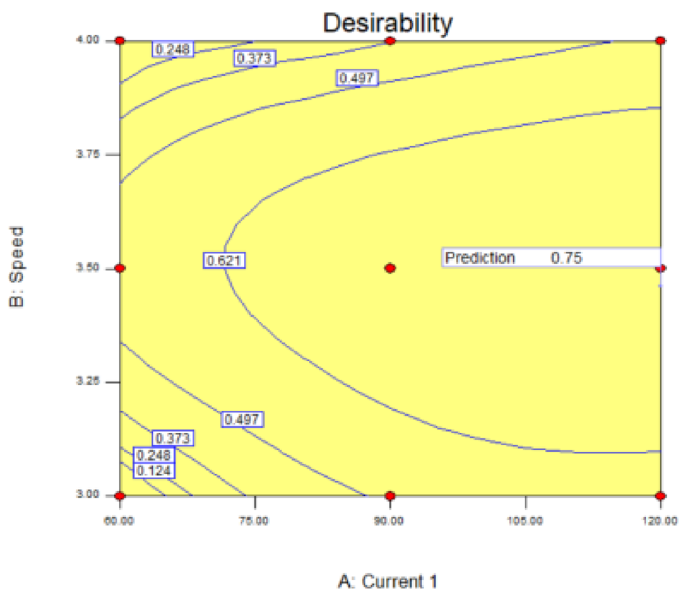


Figure 6. Contour graph of desirability index.

4.3 Validation of Optimization Model

This section discussed the result of qualification run using optimized parameter as proposed at section 4.2 assisted by modified mechanical shielding. This is to validate the effectiveness of mechanical shielding and new process parameter in production run to meet the desired target. Table 8 shows the parameter used to build the qualification lot.

Table 8 Initial and Optimized Parameter Setting

Setting	Current (Amp)	Speed (m/min)	Modified Shielding
Initial Parameter	75	4.00	None
Optimised Parameter	120	3.46	With modified shielding

Figure 7 shows the comparison of plating thickness measurement distribution on Lead1 and Lead2. There is significant improvement of Cpk on lead, improvement from 1.56 using old parameter to 2.01 using new parameter because thickness distribution has been shifted away from USL (15 um) towards centre line. This phenomenon shows new current setting and modified shielding reduce the Lead Sn thickness to even up the overall Sn thickness. Although the Cpk achievement is slightly lower from the predicted model. This is common due to various factor and uncontrollable variable in electroplating process such as chemical concentration [7-9]. Despite of this, stable Cpk is achieved and meeting the minimum Cpk 1.50 requirement at all measurement points leads. Further test on plating visual were perform to confirm its validity. At plating process, the yield is 100% without any thickness failure. Thus, new setting parameter has positive result on plating visual.

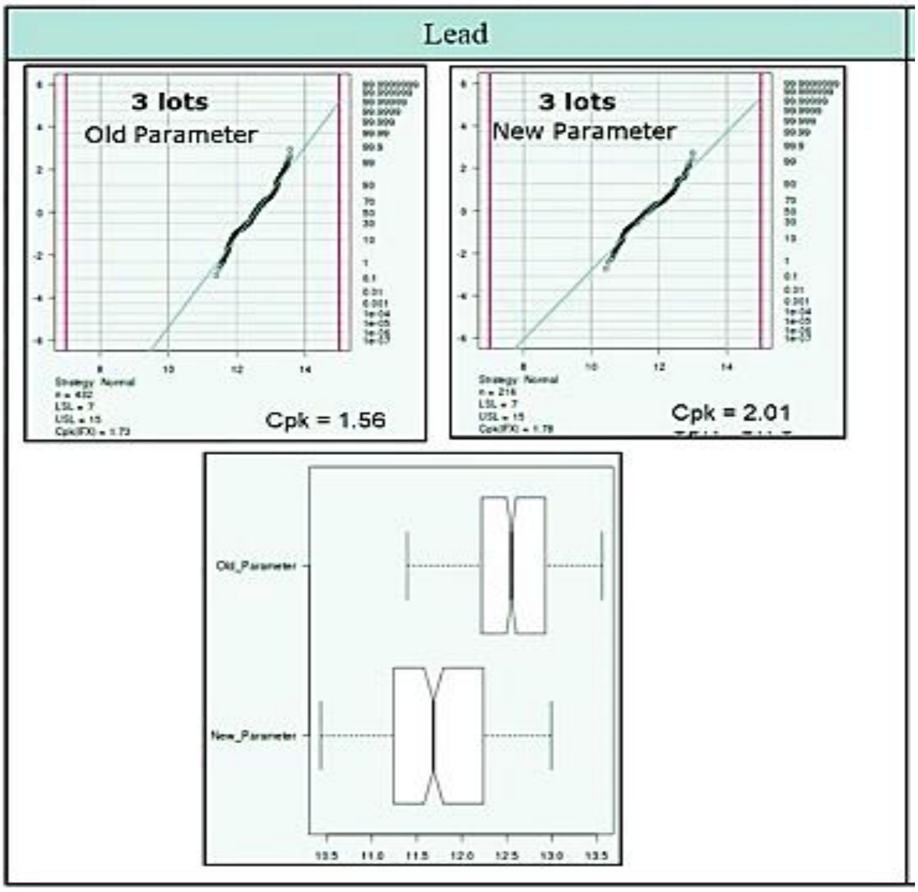


Figure 7. Comparison plating thickness distribution using old and new parameter.

Based on test yield trend shows in Figure 8, test yield is more than 95% for all three qualification lots (PASSED). There is no significant difference between qualification lot and production test yield. In summary, all qualification lot plated using newly established optimize parameter assisted by modified shielding successfully produced uniform plating thickness with Cpk improvement slightly on lead from 1.73 to 1.78.

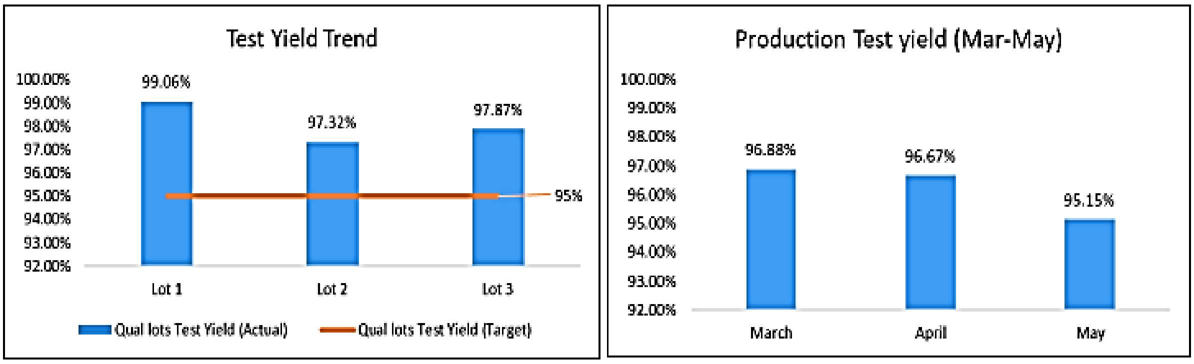


Figure 8. Test yield trend of qualification IoT.

Based on Figure 9, uniformed plating thickness deposition produced finer and uniform Sn-grain size compare with unit plated using old parameter which is known to have uneven plating thickness. Uniform grain size is important for some form of whisker growth prevention as claimed by [10]. Table 9 shows the FESEM images of Sn-grain size measurement, evident of uniform plating thickness produced finer and uniform grain size.

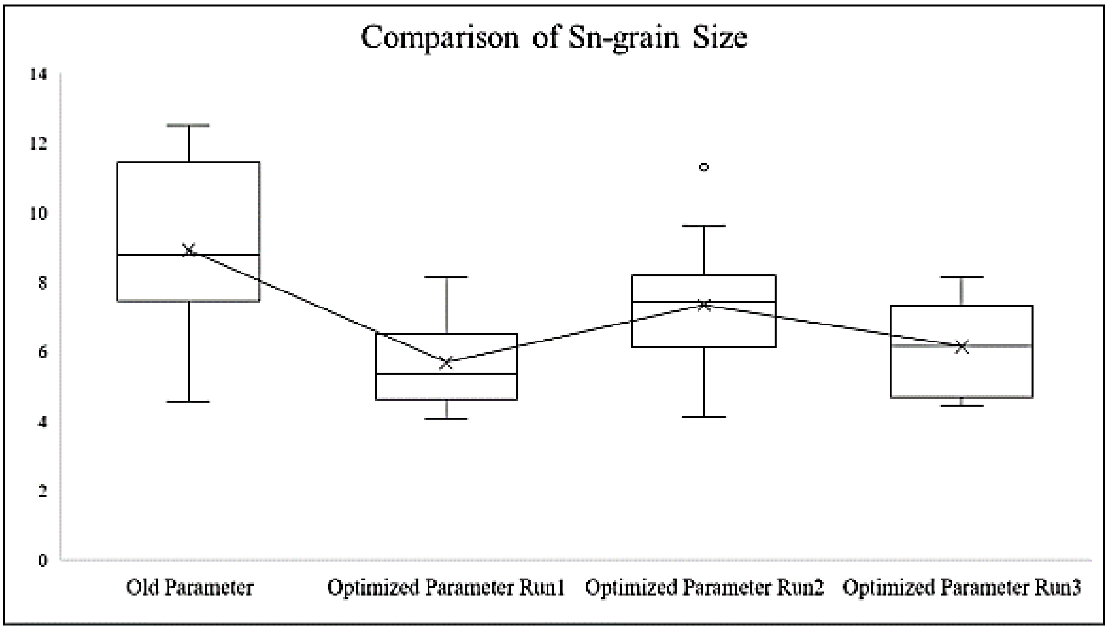
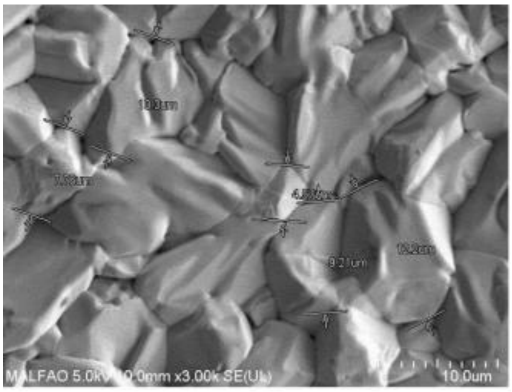
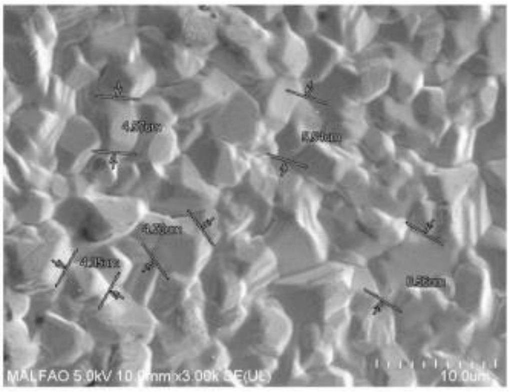
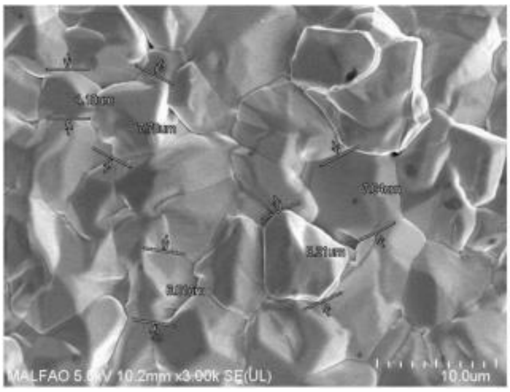
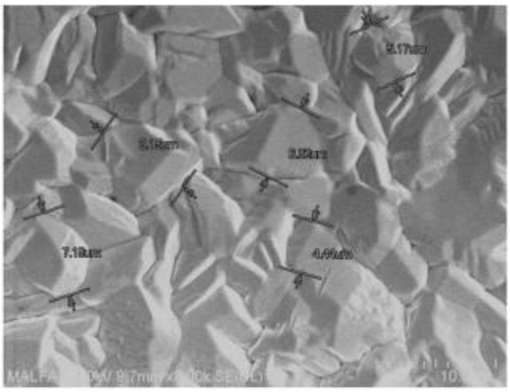


Figure 9. Comparison of Sn-grain Size.

Detailed microstructural analysis of the electroplated Sn films showed that unique pyramid shaped features formed and the underlying surface became increasingly smooth with the optimized parameter. It shows that, the correct parameter setting also affected the morphology of the whiskers that formed [11-13]. It was also observed that the diameter and length of each whisker depend on the Sn grain size. At high current density, the Sn grain form sharper and more compact surface is seen as compared to lower current.

Table 9 FESEM Images of Sn-grain Size Measurement

	
Grain size measurements 'Initial Parameter' sample	Grain size measurements 'Optimized Parameter Run1' sample
	
Grain size measurements 'Optimized Parameter Run2' sample	Grain size measurements 'Optimized Parameter Run3' sample

The increased supply of Sn ions at higher current density facilitates the decrease in sharp edges and smaller of Sn grains. The surface morphology of the samples is change with different current densities because nucleation is driven by the rate transferring of ions onto the substrate. It was observed that the optimized parameter sample has smooth and compact morphology surfaces than the initial sample i.e. the higher current density resulting in a high crystal nucleation rate that leads to a fine-grain structure. The fine-grained structure leads to a tremendous large amount of grain boundary, resulting in higher resistivity and rigidity [14]. A similar morphology is found in the other's research and it has been plated copper onto aluminum with current density1 A/dm^2. [15].

5. CONCLUSION

Within this study, optimizing electroplating process parameter and improving Sn-plating thickness uniformity on IC package has been successfully conducted using modified shielding. The Cpk analysis revealed that overall plating thickness uniformity on leads can be obtained by optimizing the most influential parameters, current and speed. The modified shielding proven has effectively reduce the thickness variation on lead as it reduces the high current setting subject to it. Based on validation result from qualification lot run, the optimized parameter has proven able to improve plating thickness uniformity, although the Cpk achievement is slightly lower from the predicted model. This is common due to various factor and uncontrollable variable in electroplating process such as chemical concentration, etc. Despite of this, stable Cpk is achieved in long run and meeting the minimum Cpk 1.50 requirement at all measurement points leads.

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REFERENCES

[1] Kanan, M., Zaimi, M., Manaf, M., & Pham, N., Journal of Advanced Manufacturing Technology, vol. **12**, no. 1(2) (2016), pp. 79-90.
[2] Kulkarni, Santosh, and Saibal Roy, Journal of magnetism and magnetic materials, vol. **322**, no. 9-12 (2010), pp. 1592-1596.
[3] A. Sharma, C.-S. Cheon, and J. P. Jung, Journal of the Microelectronics and Packaging Society, vol. **23**, no. 4 (2016), pp. 1–6.
[4] Kelly JJ, Goods SH, Talin AA, Hachman JT., J Electrochem Soc., vol. **153**, no. 5, (2006), pp. 318–324.
[5] R. Izamshah, S.A. Suandi, M. Akmal, M. F. Jaafar, M.S. Kasim, S. Ding, Int. J. of Nanoelectronics and Materials, vol **13**, (2020) pp. 379-392.
[6] R. Izamshah, M. Akmal, M.A. Ali, & M.S. Kasim, Advances in Materials and Processing Technologies, vol. **4**, no. 2 (2017) pp. 281–295.
[7] J. G. Donaldson, Metal Finishing, vol. **97**, no. 1, (1999), pp. 642-655.
[8] R. Singleton, Metal Finishing, vol. **97**, no. 1, (1999), pp. 346– 367.
[9] W. Cavanaugh and J. Langan, Plating, vol. **57**, (1970), pp. 45-47.
[10] Y. Nakadaira et al., Proc. 2nd Int. Sym. on Environmentally Conscious Design and Inverse Manufacturing, (2001), pp. 213-218.
[11] B. Soegijono, F. B. Susetyo, E.U.M. Situmorang and Yusmaniar, Asian J. of Applied Sciences, vol. **8**, no. 4, (2020), pp. 200-207.
[12] U. Sahaym, S. L. Miller and M. G. Norton, Materials Letters, vol. **64**, no. 14, (2010), pp.1547-1550.
[13] A. Sharma, S. Bhattacharya, S. Das and K. Das, Metallurgical and Materials Transactions A, vol. **45**, (2014), pp. 4610-4622.
[14] W. Dong, J. Zhang, J. Zheng, and J. Sheng, Mater. Lett., vol. **62**, no. 10–11, (2008), pp. 1589–1591.
[15] N. Sallee, M. Cromer, and O. Vittori, Can. Metall. Q., vol. **33**, no. 2, (1994), pp. 155–162.