Design of Experiments Approach for Improving Wire Bonding Quality

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***Abstract*—This study concerned with the use Experimental Design to analyze the quality problem of IC assembly factory. This study emphasized on Wire bonding process. The characteristic, such as ball size, ball height, and ball strength were depended on the parameter in the machine setting. The objectives of this study are to determine the appropriate settings of important control factors that affect a critical quality characteristic; the new response will meet the target specification and also minimize the defective rate in the Assembly process. This experiment design was the procedure to decrease the problem of bond on lead at assembly line. In the experimental machine, it was found that setting parameter of bonding force at 40- 60 grams, bonding power at 80 – 120 pulses, bonding time 10 - 30 ms were recommended for producing and controlling the ball size, ball height, ball strength, and wire strength to have the proper value.**

***Index Terms*—Design of experiment, IC assembly manufacturing, wire bonding.**

I. Introduction

Design of experiments (DOE) is a scientific method for identifying the critical parameters associated with a process and thereby determining the optimal settings [1]. The DOE assumes that the system is composed of a set of principal variables (or parameters/factors) as inputs and as the output the response (or results) for each input configuration. The objective is to analyze how the changes in the inputs alter the response. The study is carried out for the performing of bonds characteristic at Wire bond process. Wire bonding is the process of connected the wire with the circuit inside the Integrated Circuit (IC) [2]. The wire bonding process carried out by various kind of parameter. The problem of bonding problem is happen on the wire bonding process. The parameter of wire bonding machine requires precision with properly designed and operated equipment [3].

Bonding parameters are extremely important because they control the bonding yield and reliability directly[4]. The key variables for wire bonding include Bonding force and pressure uniformity, Bonding temperature, Bonging time and Ultrasonic power. [5].

In April to September period yield of Bipolar IC is 97.92%, which had Test process yield 98.26%. The major problem is Pellet problem (1.3%) but this item cannot solve by assembly process because the pellet had imported from Japan site. Therefore the next problem, which is Front of Line (FOL) defect, will be considered. FOL defected contribute to 0.22% of total defects. And the highest problem of FOL defect is Bond on Lead (BOL) defect that is 0.14% of the total defects of FOL. Base on our production forecast demand for 6 months; the production quantity is 1.8 million pieces/month. The COPQ (Cost of Poor Quality) due to BOL is equivalent to 3.6 million baths/month. This study will aim to improve the BOL problem by 60%, which can be save 2.16 million baths/month or 25.92 million baths/year. The objectives of this study are to determine and find the optimal setting of important control factors, which affecting to a critical quality characteristic in response allow the target specification and to minimize defective rate of Assembly process.

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II. Methodology

A. Material and Equipment

The items needed for an experiment are given below.

1) Wire bonding machine
2) Raw materials
3) Digital Microscope
4) Automatic Push/Pull Test machine
5) MINITAB software program

B. Methods

The summaries of the DOE method are as follows

1) Investigation problem with background process
2) Identify potential factors
3) Perform an experiment
4) Analysis data
5) Determine the appropriate setting
6) Confirmation results

1) Investigation problem with background process

This process name is Wire bonding process. First, the technician needs to program the pattern into the wire bonding machine system. Next, the technician needs to set the parameter of wire bonding machine and used the dummy of the lead frame, which have the die for setting. The technician needs to prepare and sets the capillary and the gold wire into machine. Then he needs to load the dummy into the loader and try to bond the dummy part. After setting the parameter and used the dummy to set the capillary and gold wire, the operator will load the part, which already passed mounting process at the loader stack. The wire-bonding machine will operate by automatically running. The part will be load by lead frame to lead frame into the reel and then the machine will feed the lead frame to the area of bonding fixture. At the bonding area each of part will be bond between pad and lead until finish. After that the feeder reel will be feed the next part to the bonding fixture. Until the last piece of the lead frame already bonding, the feeder reel will feed this lead frame to the un-loader stack. Since the un-loader stack already full, the operator will take them out and keep in to the Dry box and will sampling for the part to inspect before passing to the next process.

The problem occurs because of when the QC operator (quality control operator) sampling the output from the wire bonding process to measure the characteristic of the shape of ball and ball strength value. The bond on lead problem is the most defected they found. When we look into the setting procedure of the machine, we found that the parameter setting of this machine didn't have the specific limit because in current procedure when the technician setting the parameter, he only setting by measure the value of the output and used that parameter to run for the mass production. The most important parameters, effect to Bond on Lead problem are bonding force, bonding time, US power, bonding temperature, tail length, spark gap, and torch level. Therefore, in order to make a guideline level of the machine parameter settings, these seven parameters, which are bonding force, bonding time, US power, bonding temperature, tail length, spark gap, and torch level are specified to be the factors that including in the study.

2) Identify potential factors

The classification of factors for the experiment was achieved by thorough brainstorming sasses with people from production, quality control and shop floor. At this step, potential factors can be identified by, using step by step of process investigation and common QC tool namely, Cause and Effect diagram to remove unnecessary sources of variation [6]. Basically, five major categories that are man, machine, material, method and measurement are used to start for identifying all factors that may have an effect on the moisture. Using this diagram, three factors are ultimately chosen for this study and are shown in table I. Other factors, environmental factors, properties of raw material, and capability of existing machine are beyond on control so they are excluded from this experiment. From Cause and Effect diagram the factors can be classified into three main parts, first is the key design factors (X), seconds is controllable (constant) factor (C), and the last is uncontrollable (Noise) factors. All of factors that classified by each part are listed in table I.

TABLE I: IDENTIFY FACTORS AND RESPONSE VARIABLES FOR EACH STAGE.

Key design factor (X)	Controllable factors (C)	Uncontrollable factors (N)
Process Parameter Settings Wire bonding machine -Bonding Force (A) -Bonding Time (B) -US Power (C)	Measurement -Calibration Process -Instrument Types -Instrument Efficiency -Instrument Accuracy Method -Set up method -Inspection method -Operating method -Lack of adjustment skill	Man (Operator) -Lack of inspection skill -Lack of technical skill Material -Property of raw material Environmental -Humidity -Temperature

Factors

The decision as to whether a factor should be included in the experiment as well as its appropriate levels was based on consensus with engineer, operator, technician and supplemental off-line experiments. The primary basis and reasoning used in selecting each of the three factors is show in table II.

Response and Specification allowance:

1) Ball Size: Diameter of the Ball after attached on the pad size. Specification: 20 ± 3 μm
2) Ball Height: The height of Ball. Specification: 110 ± 2 μm
3) Ball Strength:The shear between the ball and Al pad. Specification: > 100 g

We summarized all of factors and their levels in the table II.

TABLE II: IDENTIFY FACTORS AND THEIR LEVELS.

Level	Factor		
	Bonding Force (g)	Bonding Time (ms)	US Power (pulse)
Low (-)	40	10	80
Moderate (0)	50	20	100
High (+)	60	30	120

3) Perform an Experiment

Team agrees to use the full factorial design experiment to estimate all possible effects including the effects of all possible interactions that can be occurred in a real situation. Moreover, team also decides to run three levels and two replications. Total number of run in this study is equal to 3^3 * 2 (54) runs.

4) Analysis of Data

The objective of this section is to identify the influence factors that contributed to the quality characteristic [7]. Therefore, statistical and non-statistical approaches are applied in this step. All of the approaches using in this study are listed as following:

1) Conduct "eye-ball" analysis.
2) Construct Analysis of variance table.
3) Construct interaction plot
4) Determine the "importance" of factors/interactions.
5) Determine R^2

Step 1 Conduct "eye-ball" analysis

The guidelines that should be considered are listed as following:

1) Selecting experiment, which minimizes the difference between the average response and the desired target value. In this study, ball size value must be within 110 ± 2 μm, ball height must be 20 ± 3 μm, ball strength must be greater than 100 g, which these values are the middle point of customer specification.
2) Selecting the experiment that minimizes response variability. In this process, Standard Deviation is the statistical measurement that using for evaluation.

There does not exist unusual the observation so we can use this data as information to set the best settings. Refer to the specification of customer: ball size value must be within 110 ± 2 μm, ball height must be 20 ± 3 μm, ball strength must be greater than 100 g, by using a "pick the winner" technique [8], each experimental run is evaluated in light of the objective. The run, which most closely meets customer specification, is declared the winner. Run number 13, 14 (bonding force=60 g, bonding time=30 ms, US power=100 pulses) and run number 22, 23 (bonding force=60 g, bonding time=30 ms, US power=120 pulses) and run number 26, 34 (bonding force=60 g, bonding time=20 ms, US power=100 pulses) and run number 38, 42 (bonding force=60 g, bonding time=20 ms, US power=120 pulses) are the best from the 54 possible combinations with the ball height are 20 ± 3 μm, ball size are 110 ± 2 μm, and ball strength are greater than 100 g. The obvious advantage of this approach is in its simplicity. This is a briefly summary so we need statistical method to confirm this summary.

Step 2 Conduct for Analysis of variance

Statistical software namely Minitab is used to analyze data, which the result of significant test is shown in table V, 6, 7. The significant levels chosen in this experiment was 0.05, so that the confidence level is 0.95 (95%).

We separated the analysis phase in to 3 cases:

1) Analysis phase for ball height response
2) Analysis phase for ball size response
3) Analysis phase for ball strength response

The result from ANOVA table of Ball Height shows that the p-value of only one interaction terms are less than 1% which means that the null hypotheses can be rejected. We can conclude that there is a significant interaction between bonding force and bonding time at 99% C.L. And the main factor (US Power) is significant too at the 90% C.L.

The result from ANOVA table of Ball Size shows that there isn't having the interaction terms are less than 1%, which means that the null hypotheses can be accepted. So we can conclude that there is a significant for main effect (bonding force, bonding time, and US power) at 99% C.L.

The result from ANOVA table of Ball Strength shows that the p-values of two interaction terms are less than 1%, and one interaction terms are less than 5%, which means that the null hypotheses can be rejected. So we can conclude that there is a significant interaction between bonding force and bonding time, bonding force and US power at 99% C.L. And there is a significant interaction between bonding time and US power at 95%C.L.

The hierarchy rule for modeling dictates that if a higher order term (interaction) include in the model, then all linear effects represented in the higher order term will be included in the model regardless of their significance. In this experiment, the inclusion of the bonding force and bonding time, bonding force and US power and bonding time and US power as important effect dictate that the main factors which are bonding force, bonding time and US power are also significant.

Step 3 Construct interaction plot

To assist in interpreting the results of this experiment, it is helpful to construct a graph of the average response at each treatment combination. For Ball Height Response: the average ball height values are shown in table III and main effect plot and interaction plots are shown in figure 1 & 2

TABLE III: AVERAGE BALL HEIGHT VALUES OF 2 WAY-INTERACTIONS

Bonding Time (ms)	Bonding Force (g)		
	40	50	60
10	34.70	28.56	25.31
20	27.52	25.59	21.71
30	24.74	23.07	21.92

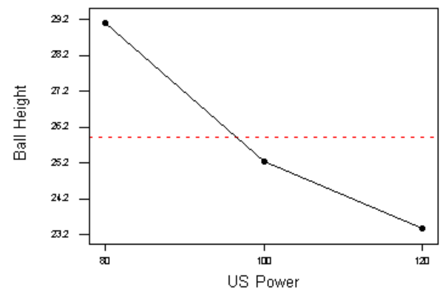

Fig. 1. US power main effect plot for the ball height response interaction plot – data means for ball height.

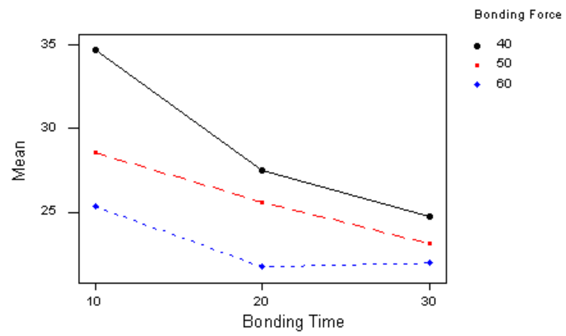

Fig. 2. Bonding force – bonding time interaction plot for the ball height response.

For Ball Size Response: the average ball size values are shown in table IV and main effect plot are shown in figure 3, 4, and 5.

TABLE IV: AVERAGE BALL SIZE VALUES OF MAIN EFFECT PLOT

Bonding Force (g)			Bonding Time (ms)			US Power (pulse)		
40	50	60	10	20	30	80	100	120
92	96	99	90	97	100	90	96	101

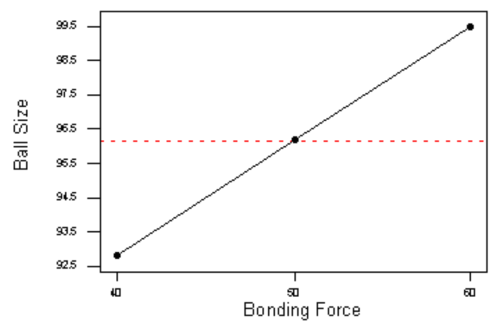

Fig. 3. Bonding force main effect plot for the ball size response.

For Ball Strength Response: the average ball Strength values are shown in table V and VI and interaction plots are shown in figure 6 and 7

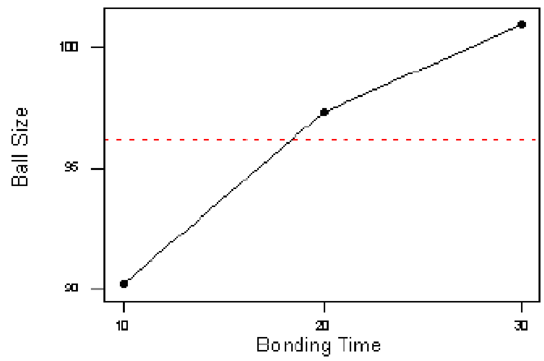

Fig.4. Bonding Time main effect plot for the Ball Size response.

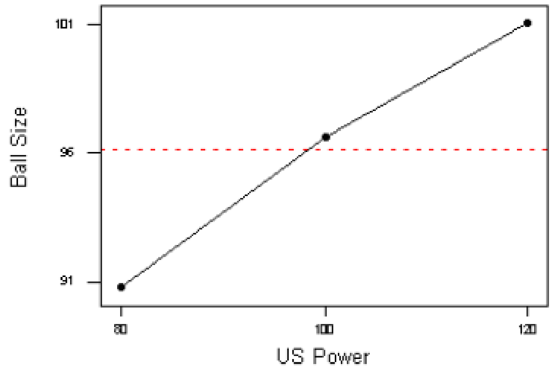

Fig. 5. US Power main effect plot for the Ball Size response.

TABLE V: AVERAGE BALL STRENGTH VALUES OF 2 WAY-INTERACTIONS

Bonding Force (g)	Bonding Time (ms)		
	10	20	30
40	55.91	70.84	83.81
50	60.90	92.95	101.01
60	76.35	99.43	115.67

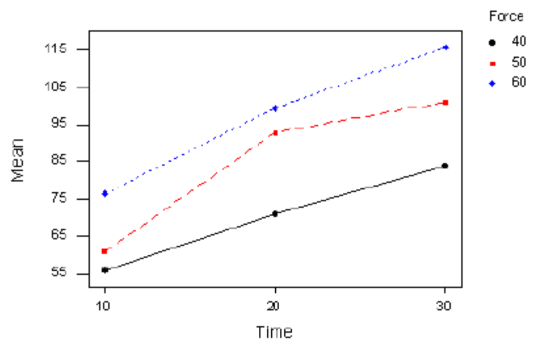

Fig. 6. Bonding Force – Bonding Time interaction plot for the Ball Strength response

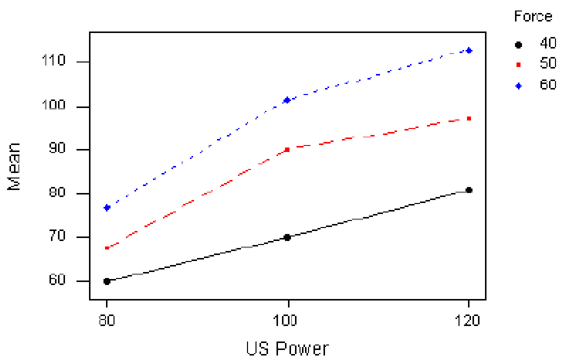

Fig. 7. Bonding force – us power interaction plot for the ball strength response.

Step 4 Determine the important factors/interactions

In this step, all information from the previous sections is applied to select the most desirable factors.

For Ball Height Response:

From table III, only one combination and one main effect are significant. From figure 1&2 also indicate the significant interaction by the lack of parallelism of the lines. Thus, the significant interaction terms are bonding force and bonding time.

For Ball Size Response:

From table IV, all three main effects are significant. From figure 3, 4, and 5 also indicate the significant of main effect that are bonding force, bonding time, and US power.

For Ball Strength Response:

From table V, three combinations are significant. From figure 6 and 7 indicate the significant interaction by the lack of parallelism of the lines. Thus, the significant interaction terms are bonding force – bonding time, bonding force – US power, and bonding time – US power interactions.

Once the significant main factors, and their combination terms are identified. The best process parameter setting can be specified by using "pick up the winner" technique. The run, which minimizes response variability and the difference between the average response and the desired target value, is specified as the best setting. The process will start by picking up 4 runs that provide the average of ball height, ball size, and ball strength values close to the specification of customer. Then, select the run that gives the lowest variability.

From the results of these four runs, run number 22, 23 (bonding force=60 g, bonding time=30 ms, US power=120 pulses) is the best of the 54 possible combinations. This run produces an average value of the ball height, 20.31 µm; ball size 108.86 µm; ball strength 127.5 g.

Step 5 Determine R^2

In addition to the basic analysis of variance,

For R-Square of Ball Height Response: R^2 = 0.743

That is, about 74.3 percent of the variability in the Ball Height is explained by bonding force, bonding time, and US power and bonding force – bonding time, bonding force – US power, bonding time – US power, and bonding force – bonding time – US power interactions.

For R-Square of Ball Size Response: R^2 = 0.9370

That is, about 93.70 percent of the variability in the Ball Height is explained by bonding force, bonding time, and US power and bonding force – bonding time, bonding force – US power, bonding time – US power, and bonding force – bonding time – US power interactions.

For R-Square of Ball Size Response: R^2 = 0.9588

That is, about 95.88 percent of the variability in the Ball Height is explained by bonding force, bonding time, and US power and bonding force – bonding time, bonding force – US power, bonding time – US power, and bonding force – bonding time – US power interactions.

1) Determine the appropriate Setting

The appropriated settings for influence factors in this experiment are summarized in table VI.

5) Confirmation Result

Therefore, 15 replication runs with the same parameter settings are conducted. After we compare the response variables from the confirmation runs with the specification from the customer, we can conclude that all of response variables pass the specification. It appears reasonable to conclude that confirmation test verified the assumptions and model. After setting the appropriate setting parameter and run for the mass production, the yield at Test process increasing from 98.26% to 98.34%. The bond on lead problem at Test process decreased to 0.059%.

TABLE VI: THE APPROPRIATE SETTINGS FOR INFLUENCED FACTORS FOR THREE RESPONSES (BONDING FORCE, BONDING TIME, AND US POWER)

<table>
<tr><th>Factor</th><th>The appropriated settings</th><th>Ball Height (µm)</th><th>Ball Size (µm)</th><th>Ball Strength (g)</th></tr>
<tr><td>Bonding Force (g)</td><td>60 g</td><td rowspan="3">20 µm</td><td rowspan="3">110 µm</td><td rowspan="3">> 100 g</td></tr>
<tr><td>Bonding Time (ms)</td><td>30 ms</td></tr>
<tr><td>US Power (pulse)</td><td></td></tr>
</table>

III. CONCLUSION

In conclusion, all of samples are passed customer specification. The average of ball height equals to 20.1 µm with standard deviation 0.4699, ball size equals to 109.95 µm with standard deviation 0.503, and ball strength equals to 127.47 g with the standard deviation 0.398 at bonding force 60 g, bonding height 30 ms, and US power 120 pulses settings. This study is aimed to determine and find the optimal setting of important control factors, which affecting to a critical quality characteristic in response (ball height, ball size, and ball strength) allow the target specification. Its investigation involves in main factors such as bonding force, bonding time, and US power. The data of each factor has been collected and tabulated using the Full Factorial Design Matrix with 2 replications in each run. The statistic technique namely, ANOVA is used in analysis decision-making process to identify the combination terms and important factors that have an effect on the critical quality characteristic in response [10]. There are ball height, ball size, and ball strength. For ball height response, only on combination and one main effect are significant. The significant interaction terms are bonding force and bonding time. For ball size response, all three main effects are significant that are bonding force, bonding time, and US power. For ball strength response, three combinations are significant. The significant interaction terms are bonding force – bonding time, bonding force – US power, and bonding time – US power interactions. From these three factors, we can understand that if bonding force, bonding time and US power are increasing, will get the higher value of ball height, ball size and ball strength.

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