Process Capability Optimization of Ball Bonding Using Response Surface Analysis in Light Emitting Diode(LED) Wire Bonding

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반응 표면 분석법을 이용한 Light Emitting Diode(LED) wire bonding 용 Ball Bonding 공정 최적화에 관한 연구

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Abstract In light emitting diode (LED) chip packaging, wire bonding is an important process that connects the LED chip on the lead frame pad with the Au wire and enables electrical operation for the next process. The wire bonding process is divided by two types: thermo compression bonding and ultrasonic bonding. Generally, the wire bonding process consists of three steps: 1st ball bonding that bonds the shape of the ball on the LED chip electrode, looping process that hangs the wire toward another connecting part with a loop shape, and 2nd stitch bonding that forms and bonds to another electrode. This study analyzed the factors affecting the LED die bonding processes to optimize the process capability that bonds a small Zener diode chip on the PLCC (plastic-leaded chip-carrier) LED package frame, and then applied response surface analysis. The design of experiment (DOE) was established considering the five factors, three levels, and four responses by analyzing the factors. As a result, the optimal conditions that meet all the response targets can be derived.

요 약 본 와이어 본딩은 발광 다이오드의 패키징 공정에서 매우 중요한 공정으로 금 와이어를 이용하여 발광 다이오드 칩과 리드 프레임을 연결함으로써 다음 공정에서의 전기적 작동을 가능하게 한다. 와이어 본딩 공정은 얇은 금속선을 연결하는 공정으로 열 압착 본딩(thermo compression bonding)과 초음파 본딩(ultra sonic bonding)이 있다. 일반적인 와이어 본딩 공정은 LED 칩 상부 전극 부위에 볼 모양의 본딩을 진행하는 1st ball bonding 공정, loop를 형성하여 다른 전원 연결부위로 wire를 늘어뜨리는 looping 공정, 다른 전극 부위 상부에 stitch를 형성하여 bonding 하는 2nd stitch bonding으로 구분된다. 본 논문에서는 발광 다이오드 다이 본딩 공정에 영향을 주는 다양한 공정 변수에 대하여 분석을 수행하였다. 그리고 반응 표면 분석법을 통하여 Zener 다이오드 칩과 PLCC 발광 다이오드 패키지 프레임을 연결하는 공정 최적화 결과를 도출하였다. 실험 계획법은 5인자, 3수준에 대하여 설정하였으며 4가지 반응에 대하여 인자를 분석하였다. 결과적으로 본 연구에서는 모든 목표에 맞는 최적 조건을 도출하였다.

1. Introduction

A light emitting diode (LED) is a kind of luminous semiconductor device that has been applied in automotive lighting, outdoor illumination, and back-light units (BLUs) for large display panels[1-3].

LEDs have superior characteristics, such as high efficiency, low power consumption, high reliability, and long life. The LED chip packaging process goes through the following steps: a wafer inspection process to inspect the quality of the chips formed on the wafer; a die bonding process, which cuts the wafer and bonds the chips divided into pieces on the lead frame; wire bonding, which connects the contact pads installed at the die and the lead frame's Au wire; a molding process to wrap the exterior with an encapsulant to protect the die's internal circuit and other components; a trim process for connecting leads and cutting the dam bar; and a forming process that forms the leads in a desired shape. Among these processes, the wire bonding process connects thin metal wires. This process includes thermal compression bonding, which glues while applying temperature and pressure; and ultrasonic bonding, which applies ultrasonic vibration at approximately 60 kHz[4-9]. The typical wire bonding process is divided into a first ball-bonding process that conducts ball-shape bonding on the upper part electrode of the LED chip, a looping process that hangs wire to the other power supply part by forming a loop, and a second stitch bonding that bonds by forming a stitch on the upper part of another electrode.
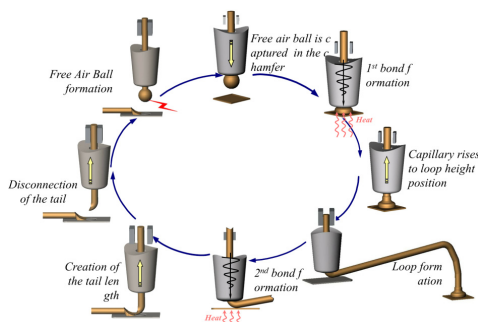

Fig. 1. Flow chart for the correction of the roll forming process design.

This research drew results by applying a design of experiment (DOE) for bonding process optimization and process capability evaluation, on the basis of the first ball bonding, which is the more core process in wire bonding. To find the optimum response between each level, this study applied the response surface design and analysis. Under the application of the response target values, important control factors' optimum values were calculated. Then, wire bonding process responses were calculated through the wire bonding process at each optimum condition, and a comparative analysis with the target values and process capability was evaluated.

2. Response Surface Analysis

The response surface analysis was first used by Box and Wilson. It is a statistical analysis of the response surface composed by response changes when several independent parameters affect a certain dependent variable through a complex reaction[10-13]. In this model, when several independent parameters, $x_1, x_2, \cdots, x_k$, undergo complex reactions, the dependent variable, y, can be modeled as follows:

$$y = f(x_1, x_2, \cdots, x_k) \tag{1}$$

As a reaction function, a typically assumed convenient and practical response surface model is the multiple regression model upon k independent parameters. The linear regression and quadric regression models having k independent parameters are

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \epsilon_i \tag{2}$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i \le j}^{k} x_i x_j + \epsilon_i \tag{3}$$

where ϵ is the error; it is assumed to follow the (0, σ2) distribution[13].

3. Wire Bonding Process Analysis

3.1 Wire Bonding Process Analysis and Important Control Factors Extraction

Generally, after the stitch bonding of Au wire, discharging the electric arc by applying high voltage and weak current between the cut wire and the electronic flame off (EFO) band, and melting the end of the Au wire in a ball shape, a free air ball (FAB) is formed by surface tension as coagulation is generated; this sets up the first ball bonding in the wire bonding process. Then, the first ball bonding is carried out by applying ultra-sound and pressure through capillary action in terms of the ball on the upper part electrode of the chip.

Table 1. Process control parameters for first ball bonding.

Parameter	Min.	Ave.	Max.
Ultrasonic generator operating voltage (mV)	-	3,500	-
Ultrasonic generator operating current (mA)	50	140	200
Ultrasonic generator operating time (ms)	2	13	25
Ultrasonic generator adoption power factor (%)	20	85	150
Forcing power (g)	10	40	80
FAB(free air ball) size (Mil.)	1	2.3	3
EFO(electrical flame off) operating current (mA)	5	30	50
Gap between FAB and electrical flame (Mil.)	5	30	50

Table 1 shows the important control factors related to such a wire bonding process. Table 2 exhibits five factors that most affect the first ball bonding process results, in consideration of the experiences of equipment developers and operators and the equipment operation mechanism. As core factors, the ultrasonic generator (USG) operating current, USG bond time, force, FAB size, and EFO current are extracted.

Table 2. Important process control parameters for first ball bonding.

Parameter	Min.	Ave.	Max.	Abbreviation
Ultrasonic generator operating current (mA)	50	140	200	USGC
Ultrasonic generator operating time (ms)	2	13	25	USBT
Forcing power (G)	10	40	80	FORC
FAB(free air ball) size (Mil.)	1	2.3	3	FABS
EFO(electrical flame off) operating current (mA)	5	30	50	EFOC

3.2 Determination of Wire Bonding Process Response Values

The responses that represent the first ball bonding in the wire bonding process are ball dimensions (ball size and ball height), ball strength (ball shear strength and bonding area), and bonding position precision. Table 3 shows each parameter's target to be achieved through this research.

Table 3. Response and target values of first ball bonding process

Parameter	Target	Abbreviation
Ball Shear Strength (gf)	>30	BSS
Ball Height	15±5	BH
Ball Size	80±6	BS
Position Precision	±20	PP
Bonding Area (%)	>30	BA

4. Wire Bonding Process Analysis

4.1 Application of Design of Experiment

This research conducted a die bonding process, a previous process of wire bonding by preparing an LED package frame with 24 rows and 14 columns, a medium output horizontal LED chip, a Zener diode chip (ODTech, 200×200×100 ㎛), transparent silicon resin adhesive (Dow Corning, OE8002), and Ag paste (Sumitomo metal mining, T-3100) as shown in Fig. 1.
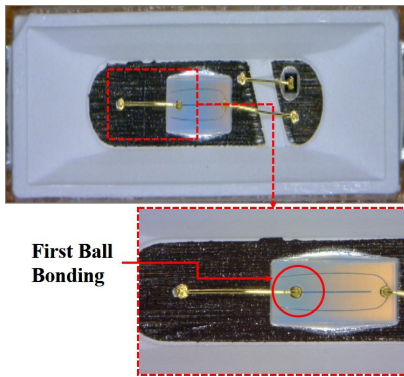
Fig. 2. Work materials used for LED package wire bonding.

Transparent silicon resin was used for the output horizontal LED chip used in die bonding, and conducive Ag paste was used for the Zener diode chip in die bonding. As derived previously for the application of the DOE in the wire bonding process, the DOE was established in consideration of five factors, three levels, and four responses. The types of experiments to be conducted numbered 46, and each experiment was repeated five times. Therefore, total number of experiments was 230 (230 packages). The DOE in wire bonding process was analyzed by using a commercial software Minitab R16 (Minitab Inc., USA).

4.2 Wire Bonding Experiment and Results

This study conducted the first ball bonding experiment in the wire bonding process under the experimental conditions mentioned previously, and the responses of ball shear strength (BSS), ball height (BH), ball size (BS), ball position precision (PP), and ball area (BA) were analyzed. And then setup criterion values for normal or abnormal decision about ball size (BS), ball position precision (PP), and ball area (BA) etc. as shown in Fig. 4. For measuring value of size about BS and PP using the machine vision system. Because the PP result among the first ball bonding responses was included within the target value ±20 mm as shown in Fig. 4, this study conducted a response

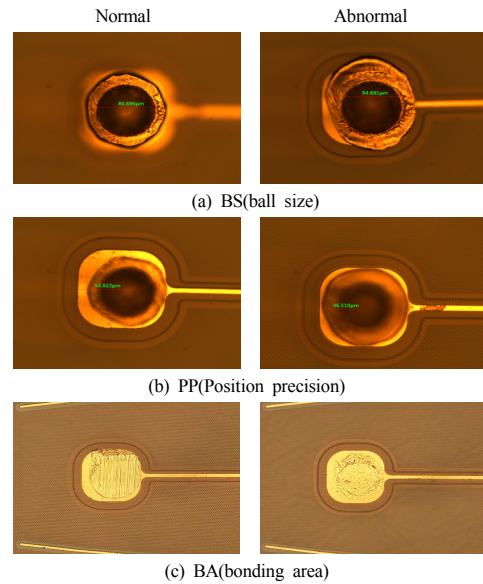surface analysis on the remaining four responses; Fig. 5 shows the results.

Normal   Abnormal

(a) BS(ball size)

(b) PP(Position precision)

(c) BA(bonding area)

Fig. 3. The setup criterion values for normal or abnormal decision in first ball bonding process.

Fig. 4. Position precision summary.

(a) Ball Shear Strength (BSS)

(b) Ball Height (BH)

(c) Ball Size (BS)

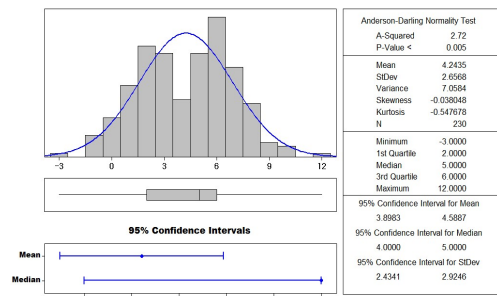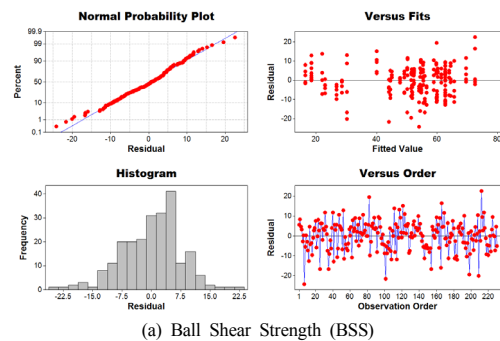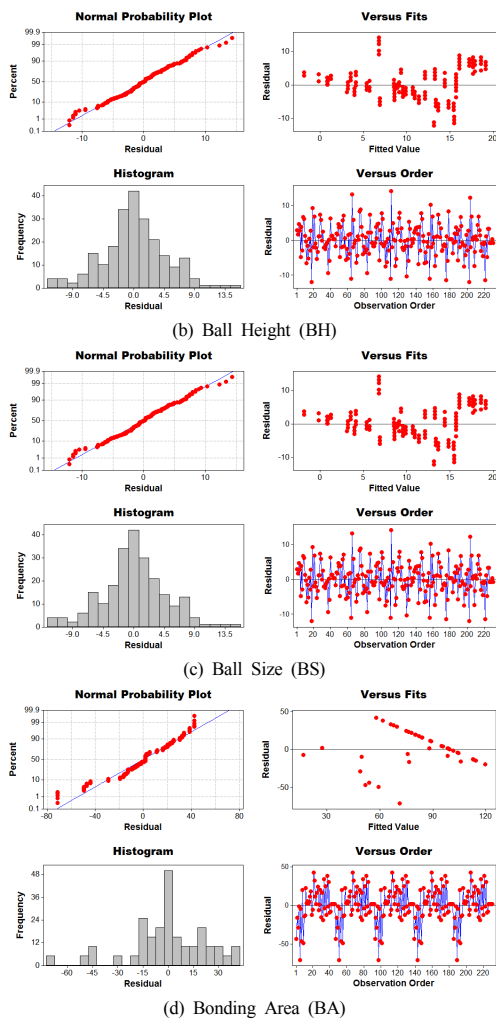(d) Bonding Area (BA)

Fig. 5. Residual plot of BSS, BH, BS, BA.

4.3 Experimental Analysis and Drawing Optimum Conditions

After the response surface analysis of the important process factors, this study drew tentative optimum conditions by additionally using a response optimization tool. This study adjusted the tentative optimum conditions through the integer of the derived tentative optimum conditions, and five responses (BSS, BH, BS, PP, and BA) were forecast to achieve targets. Thus, additional verification experiments were carried out with these conditions. This research conducted verification by carrying out the first ball bonding

process for 30 packages under the derived tentative optimum conditions and evaluated the process capability by each response. The response distribution results under the tentative optimum conditions are shown in Fig. 6. From the derived tentative optimum conditions, all responses achieved the targets. The ultimately derived optimum conditions are shown in Table 4, and in Fig. 7.
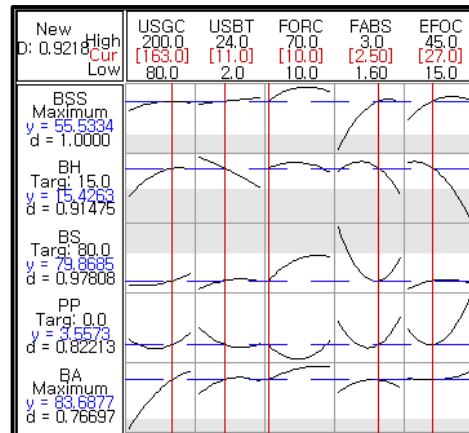

Fig. 6. Response distributions at tentative optimum conditions.

Table 4. Derived optimal conditions for first ball bonding.

Parameter	Optimal values	Abbreviation
Ultrasonic generator operating current (mA)	163	USGC
Ultrasonic generator operating time (ms)	11	USBT
Forcing power (G)	10	FORC
FAB(free air ball) size (Mil.)	2.5	FABS
EFO(electrical flame off) operating current (mA)	27	EFOC

(a) BSS(ball shear strength)

(b) BH(ball height)
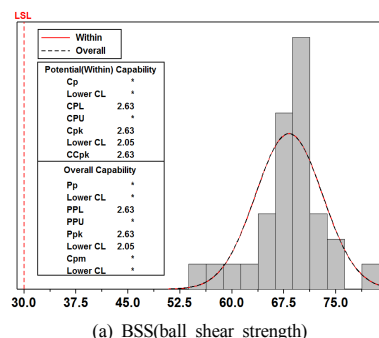
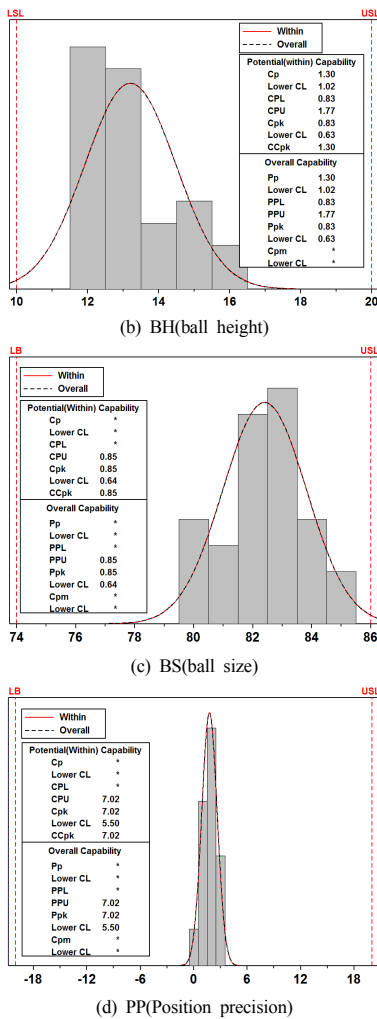

(c) BS(ball size)

(d) PP(Position precision)

Fig. 7. Process capabilities of ball shear strength, ball height, ball size, position precision, and bonding area at tentative optimum conditions.

As a result of evaluating the process capabilities under the derived optimum conditions, the defect rate was 0% in all the responses, from actual observations. However, the defect rates of BSS, BH, BS, PP and BA were 2.63%, 0.83%, 0.85%, 7.02% and less than 10%, respectively. All these were forecast to be 0%, 0.62%, 0.55%, 0%, and 0%, respectively. It is considered that the difference of defect rates is generated by unexpected error of experiment or design.

5. Conclusions

This research conducted a first ball bonding optimization experiment among the wire bonding processes that connect the LED chip and pad, after a die bonding process on the LED package frame was conducted by applying a response surface analysis. The optimization of the five important control factors (USG current, USG bond time, force, FAB size, and EFO current) to achieve the targets of the responses (Ball shear strength (BSS), ball height (BH), ball size (BS), ball position precision (PP), and bonding area (BA)) of the first ball bonding process, which is a representative core process of wire bonding, was conducted through the response surface design and analysis. The results are as follows:

(1) Through the response surface design and analysis, the optimum conditions of the first ball bonding process of wire bonding were 163 mA of USG current, 11 ms of USG bond time, gf of force, 2.5 mil of FAB size, and 27 mA of EFO current.

(2) As a result of evaluating the process capabilities by deriving a short-term process capability index (Cpk) under the optimum conditions, the defect rate was 0% in all responses, from actual observation. However, the tentative defect rates of the short-term process were forecast to be 0% for BS, 0.62% for BH, 0.55% for BS, 0% for PP and 0% for BA. In this regard, only BSS, PP and BA were concluded to have short-term process capabilities at the 6-sigma level. Further study about this research is needed for more correct results.

Acknowledgment

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