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Optimization of the Cu wire bonding process for IC assembly using Taguchi methods

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ABSTRACT

The yield of IC assembly manufacturing is dependent on wire bonding. Recently, the semiconductor industry demands smaller IC designs and higher performance requirements. As such, bonding wires must be stronger, finer, and more solid. The cost of gold is continuously appreciating, and this has become a key issue in IC assembly and design. Copper wire bonding is an alternative solution to this problem. It is expected to be superior over Au wires in terms of cost, quality, and fine-pitch bonding pad design. To obtain the best wire bonding quality, we employed Taguchi methods in optimizing the Cu wire bonding process. With Cu wire bonding technology, the production yield increased from 98.5% to 99.3% and brought approximately USD 0.7 million in savings.

1. Introduction

The key to a good quality IC assembly is wire bonding. Gold has been widely used in conventional wire bonding. However, more and more IC manufacturers are switching from Au to Cu to reduce material and production cost, gain better conductivity, and establish better mechanical properties. According to estimates, replacing Au with Cu can save more than 10% of the total IC assembly cost, and Cu wire bonding easily cuts production costs, creating an obvious advantage in revenue generation. In addition, the electrical conductivity of Cu is better than that of Au or Al, increasing the effectiveness and reliability of the manufactured IC devices. In order to enhance thermal dissipation and wattage, Cu wires with relatively small diameters (e.g., 0.7 mil) can be used as conducting wires in the bonding process. Besides, the mechanical properties of Cu are better than those of Au. The use of Cu firms up the neck region of bonding balls and provides high stability of wire loops in the molding process. To achieve better market shares and maintain relationships with clients, manufacturers are devoted to improving the capabilities of Cu wire bonding. It is neither a new technology nor a new observation in material development. Although Cu has already been applied for wire bonding over the past 10 years, its mainstream use remains difficult. Issues concerning the process of Cu wire bonding are related to metallic compounds of Cu and Al (e.g., oxidation and expansion properties and reliability). Therefore, the optimization of the parameter settings for successful Cu wire bonding is especially crucial for IC assembly and design.

In this study, a Taiwanese IC assembly manufacturer was required by a client to use Cu wires in wire bonding stations, instead of Au wires. They, however, lacked experience in setting the controllable parameters for successful Cu wire bonding. Consequently, in the initial stage of Cu wire bonding, only a 98.5% yield was achieved. Yield is the ratio of qualified products at the end of a wire bonding process to the number of products submitted for processing.

Copper wire bonding is complex because it involves the risk of oxidation, which affects the quality of Cu wire bonds. Techniques or parameters that are used or modified to prevent oxidation include bonding current (power), bonding time, bonding voltage (force), temperature of the heat block, and nitrogen atmosphere. Some examples of studies showing how bonding parameters affect the bonding quality can be found in [1]. Parameter optimization involves multivariable considerations, making it difficult and complicated. With multivariable considerations, it is impossible to adjust a single parameter without affecting the others. In practice, the parameter design of Cu wire bonding still relies heavily on the experience and knowledge of engineers, and it involves trial-and-error experimentations. Inexperience and lack of knowledge always result in the loss of time and material resources.

Taguchi methods are a system of cost-driven quality engineering that emphasizes the effective application of engineering strategies rather than advanced statistical techniques. They have been widely and successfully used for determining the optimum process parameters in many applications because of their simplicity [1–7]. Because of these reasons, this study employs Taguchi's approach to optimize the Cu wire bonding process during IC assembly.

Section 2 of this paper briefly describes the Cu wire bonding process. Section 3 presents Taguchi's approach to parameter

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optimization. Section 4 details the implementation of Taguchi's approach to the optimization of parameter settings for Cu wire bonding. Finally, the conclusion is given in Section 5.

2. Cu wire bonding process of IC assembly

2.1. IC assembly flow and wire bonding

There are four types of conducting bond pads connected to lead frame or substrates in the process of IC assembly, namely, Al wires, Au wires, Au or Solder bumps, and Cu wires. In newly established noble metal markets, Cu wire bonding is gradually becoming a mainstream technique. Cu wires are relatively cheaper, and they have good conductivity and mechanical properties. They can also reduce bonding costs during assembly.

The process for IC assembly is shown in Figs. 2.1a and 2.1b. The primary characteristics of the bonding process are shown in Fig. 2.2. Wire bonding involves mechanical energy transfer through ultrasonic energy. Both ultrasonic oscillation and thermosonic bonding are adopted by the bonding machine. The Cu ball connects with the Al die pad using heat and pressure. The interface of the Cu ball and Al pad are cleaned before beginning the process. In order to enhance the activation energy of each atom, the bonding force and bonding current, which caused the Cu ball to bond with the Al pad, are controlled. Both bonding force and bonding current are key factors for the 1_st bond. For the 2_nd bond, both Tip (Tip diameter) and capillary/velocity (C/V) are key factors. In the second bonding position, the speed of the bonding capillary decreases with uniform velocity. During the bonding process, power, time, and force interact to reduce the impact of forces acting on the material and wastage on bonding capillaries.

The wire bonding process involves two items, namely, the wire bonder and the bonding wire (i.e., Au or Cu). The wire bonder is provided by the equipment supplier. The assembly manufacturer only selects a machine model. Selection of the bonding wires is based on the bonding pad design from the design manufacturer. Bonding quality significantly affects the yield and reliability of the products. In addition, market shares influence in the bonding process. For these reasons, assembly manufacturers seek to apply more stable bonding machines and bonding wires. To this end, the Cu wire bonding technology presents a promising alternative.

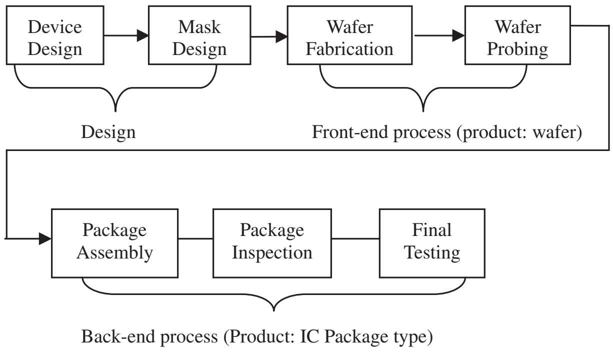

Fig. 2.1a. Semiconductor LSI process (large scale integration).

2.2. Cu wire bonding

In general, to judge the wire bonding ability, we control the bonding ball shear and the bonding wire pull (Fig. 2.3). Value settings differ according to the type of assembly package. Moreover, wire diameters also differ depending on whether Au or Cu was used. In order to ensure high quality bonding, several operational parameters in the bonding process must be systematically tuned. However, because of inexperience and lack of references in Cu wire bonding, non-optimal parameter settings have been used previously, resulting in poor performance. High quality Cu wire bonding and optimized bonding yield rates are determined by adjusting the process parameters. Fig. 2.4 shows the wire bonding (engineering) step.

3. Taguchi methods for parameter optimization

3.1. Taguchi methods

In practice, parameter optimization is of primary importance in wire bonding, especially when a new system or material change is introduced and implemented. Parameter design problems are complex, and nonlinear relationships and interactions may occur among parameters. Hence, engineers frequently encounter difficulty in determining process parameters for product development, process design, and operational condition setting.

Taguchi methods combine experimental design techniques with quality considerations. Taguchi methods carefully consider the impact of various factors influencing variations in performance. They consist of three phases: (1) system design, (2) parameter design, and (3) tolerance design. A more detailed description of these three design phases is provided by Kackar [13] and Phadke [14]. The parameter design phase is crucial in improving the uniformity of the products.

Design parameters (i.e., factors that are controlled by designers) and noise factors (i.e., factors that cannot be controlled by designers, such as environmental factors) influence the quality (i.e., responses) of a system. The Taguchi methods involve selecting levels of design parameters to minimize the effects of noise. In other words, design parameters for a product or a process are selected to achieve minimum variation in product response and to remain close to the desired target.

In Taguchi's parameter design approach, an experimental design was first used to arrange the design parameters (i.e., control factors) and noise factors in orthogonal arrays. Subsequently, the signal-to-noise (*SN*) ratio was computed for each experimental combination. The *SN* ratios were then analyzed on the basis of quality loss to determine the optimal design parameters. In this study, only the static quality characteristic problem is discussed, in which the desired response value is fixed. Taguchi [15] suggested the use of the following *SN* ratios:

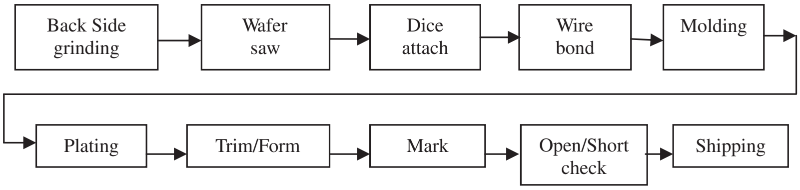

Fig. 2.1b. IC assembly process.

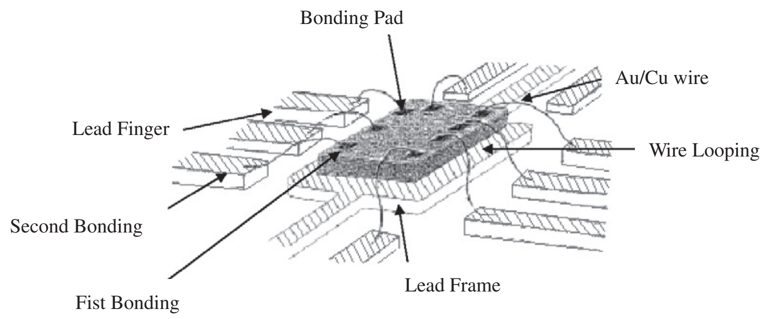

Fig. 2.2. Wire bonding.

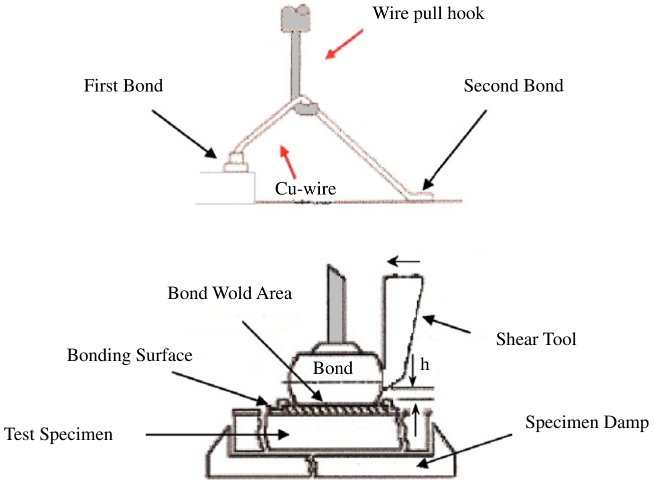

Fig. 2.3. Sketch of ball shear and wire pull (a destructive testing).

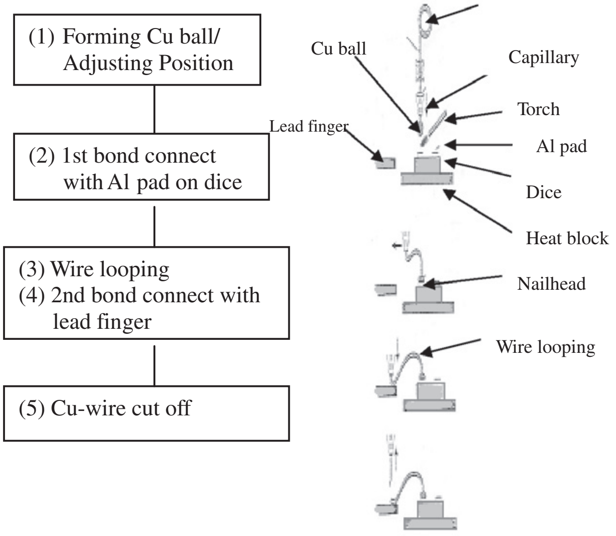

Fig. 2.4. Bonding connect engineering step.

For the-smaller-the-better characteristic,

$$SN = -10 \cdot \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

where y is the response, and n is the number of tests in a trial.

For the-larger-the-better characteristic,

$$SN = -10 \cdot \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right] \tag{2}$$

For the-nominal-the-best characteristic,

$$SN = 10 \cdot \log_{10}\left[\frac{\frac{1}{n}(S_m - V_e)}{V_e}\right] \tag{3}$$

where $S_m = \frac{1}{n}\left(\sum_{i=1}^{n} y_i\right)^2$ and $V_e = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2$.

In practice, the performance of the-smaller-the-better and the-larger-the-better characteristic problems is judging by the *SN* ratio. The higher the *SN* ratio, the better performance is. For the-nominal-the-best characteristic problem, the two-stage optimization procedure is conducting for optimizing the parameters. The two-stage procedure includes: (1) Minimize variability (maximize *SN* ratio) in the product, and (2) adjust the output to hit the target. The merits and shortcomings of the Taguchi methods can be found in [15].

3.2. Related works

Xue et al. [10] employed Taguchi methods to identify a robust design with a downstream process that is the least sensitive to changes in design parameters. Changes in design parameters are usually associated with probabilities. Hence, in this research, the Taguchi methods were modified considering the probabilities of noise parameters. Costs of process changes due to potential changes in design parameters have also estimated. Chen et al. [8] employed Taguchi methods to deal with four critical process factors in fabricating silicon nanowires to achieve the target value and reduce standard deviations in diameter. Su et al. [9] applied a response surface methodology to determine the critical parameters in the inter-metal dielectric manufacturing process to avoid the occurrence of voids, which cause electric leakage and result in losses. Tam et al. [1] employed Taguchi methods to formulate an experimental layout and to analyze the effect and predict the optimal setting of each control factor for cutting low-carbon steel sheets (4.5 mm thick) using a laser cutting process. Li et al. [2] also used Taguchi's experimental method to obtain optimal combinatorial parameters for cutting flat, quadrilateral non-lead (Quad Flat Non-Lead) packages by employing a diode-pumped solid-state laser system. Plessis et al. [11] used Taguchi's experimental design to investigate the effects of airflow rate, residence time, impeller speed, surfactant dosing, sludge dilution, and their interactions. Daneshvar et al. [12] applied Taguchi's approach to optimize experimental parameters. Above studies showed that the Taguchi's approach could be efficiently applied to solve the problem of process parameter design in the industry.

3.3. Taguchi's approach for Cu wire bonding

We propose seven steps for parameter optimization in Cu wire bonding:

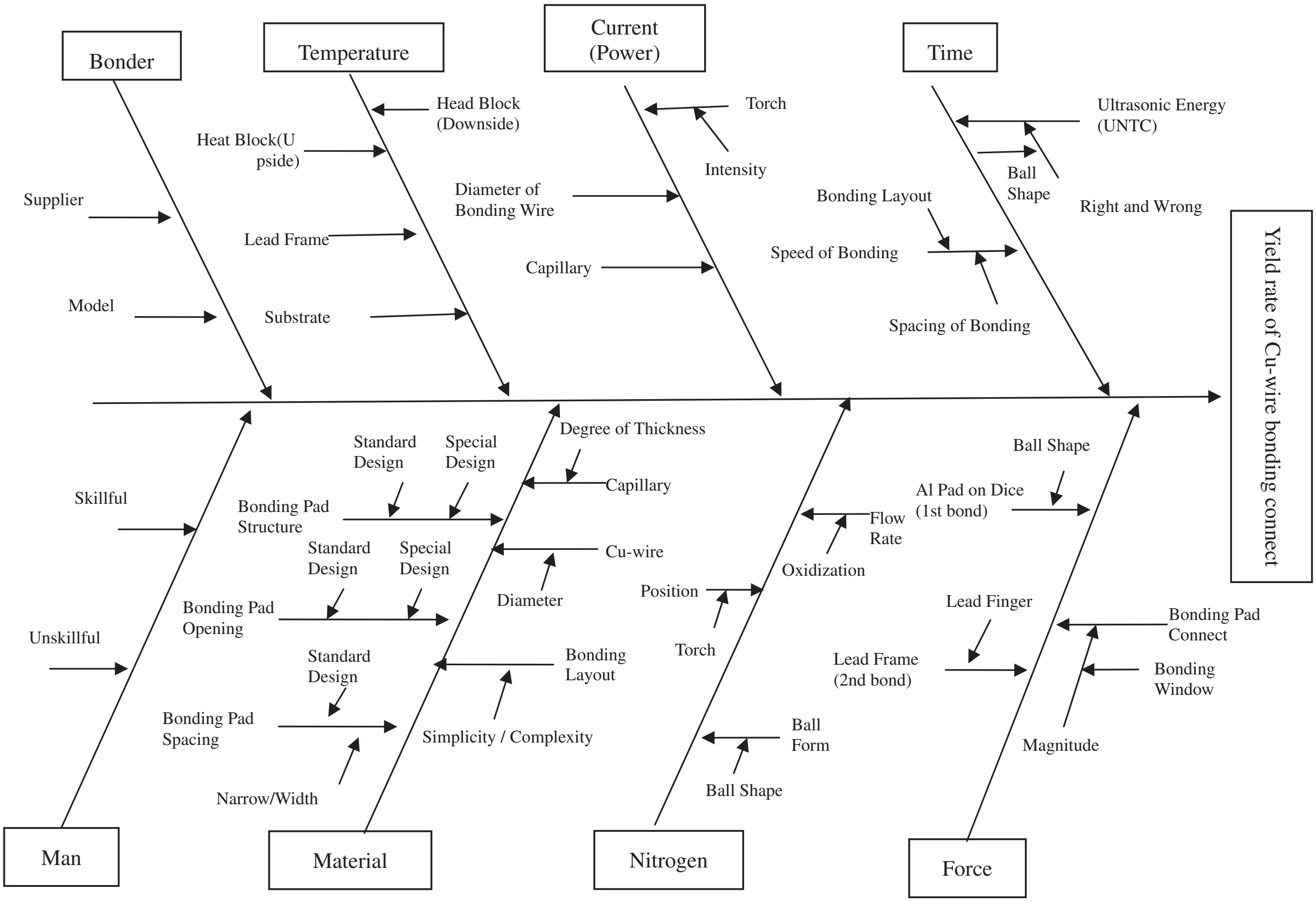

Fig. 4.1. Cause and effect diagram.

Step 1: Determination of the system's objectives, scope, and responses.

The system's objectives and scope should first be defined. Thereafter, project members and a leader are chosen. Major functions, side effects, and failure types are confirmed. With these, the response can be determined.

Step 2: Identification of noise, control factors, and their levels.

First, critical noise factors are determined and levels are set. Noise strategies are determined. Thereafter, all control factors, critical control factors, and their levels are determined.

Step 3: Experimental design

First, the orthogonal array is determined. Second, control factors are assigned to the selected orthogonal array.

Step 4: Experimentation and data collection.

After preparation, experiments are conducted and data are collected.

Step 5: Data analysis.

First, for each experiment, the *SN* ratio and $\bar{y}$ are determined. Second, the response graphs of each factor to *SN* ratio and $\bar{y}$ are completed and interpreted. Third, the optimum level combination of control factors are chosen, and the *SN* ratio and $\bar{y}$ are predicted. If the-nominal-the-best characteristic problem is solved, the two-stage optimization procedure should be performed.

Step 6: Performance of a confirmation experiment.

Taguchi recommends conducting a confirmation experiment. If the experimental results do not conform with (or satisfy) the predicted results, it indicates that the experiment has failed, and it is necessary to plan for another new experiment.

Step 7: Implementation of the optimal solution.

When the experiment is confirmed, the optimum level of control factor combination is implemented in the system.

4. Implementation

In this study, the case comes from an assembly manufacturer at the Tainan Industrial Park, Taiwan. The company encountered serious problems (e.g., loss of orders due to costs and bonding yield loss of 1.0–1.35%) with the initial introduction of Cu wire bonding. To enhance the bonding yield, Taguchi methods were applied to determine the optimal parameters.

4.1. Implementation of the Taguchi methods for Cu wire bonding

In this study, the system is focused on the product yield of the wire bonding process. Wire bonding influences 40% of the loss in product yield. We organized a project team to improve the Cu wire

Table 4.1
Control factors and their levels.

Factors	Unit	Levels		
		1	2	3
A: power	mA	62	65	68
B: time	ms	27	32	37
C: force (voltage)	g	6	8	10
D: temperature	°C	140	150	160
E: nitrogen blow	l/min	0.5	0.6	0.7

Table 4.2
L_{18} $(2^1 \times 3^7)$.

No.	Factor/level							
		A	B	C	D	E		
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

bonding process. A senior on-site engineer was selected as project leader. Yield loss was defined in terms of wire pull test failure or ball shear test failure. The wire pull test is done by having the wire pull hook to pull the Cu wire until the Cu wire breaks. The pull force is gradually adjusted, and the extreme value of the pull force that causes the wire to break is recorded as the result of wire pull test. Similarly, the ball shear test is done by having the Cu ball sheared away from the bonding pad gradually by the shear tool until the ball is removed, and the shear force which is applied to the ball that results in the removal of the ball is recorded as the result of the ball shear test. This study belongs to the larger-the-better characteristic problem.

The location of the bonding pad in the die was chosen as the noise factor. We chose 20 locations, and most of the wire sizes were considered in the experiment.

In order to speed up the experiment and to reduce complexity, a cause-effect diagram was drawn (Fig. 4.1). According to expert knowledge provided by on-site engineers, five parameters are adjustable and considered potentially influential in improving bonding quality. These five control factors are bonding power, bonding time, bonding force, bonding temperature, and nitrogen atmosphere (Table 4.1). By collecting several trial data on parameter setting and the corresponding bonding yield rates, the project team determined control factor levels based on engineering knowledge and experience.

This study considered five control factors with three levels. The orthogonal array of L_{18} $(2^1 \times 3^7)$ was employed to verify the effects of these factors on Cu wire bonding. The project team assigned control factors to the selected orthogonal array (Table 4.2). Experimental materials, including wafer, substrate, wire bonder, Cu wire, capillary, heat block, and factors/levels, were prepared. Two engineers were assigned to run the experiment. For each trial, 20 observations were collected through the wire pull and ball shear tests.

Based on the collected data (not shown), *SN* ratios were calculated for each experiment. Thereafter, the response graphs of each factor to the *SN* ratio were drawn (Fig. 4.2 for wire pull test; Fig. 4.3 for ball shear test). In addition, to provide better results for the relative effects of various factors and for a more objective way of determining the optimal condition, an analysis of variance was conducted (Tables 4.3 and 4.4). Based on the analyses, Factor *A* is the most significant among the five control factors, followed by Factors *C* and *E*. Other factors were not so important. After discussion with the engineers, the optimal condition was set at $A_3B_1C_3E_3$.

To verify the effectiveness of the optimal condition, a confirmation run was conducted. First, the addition mode was used to predict *SN* ratio under the optimum condition. The expected mean value for the wire pull is

$$\hat{\eta} = \bar{\eta} + (\bar{A}_3 - \bar{\eta}) + (\bar{C}_3 - \bar{\eta}) + (\bar{E}_3 - \bar{\eta})$$
$$= 19.75 + 19.67 + 19.68 - 2 \times 19.64 = 19.82db$$

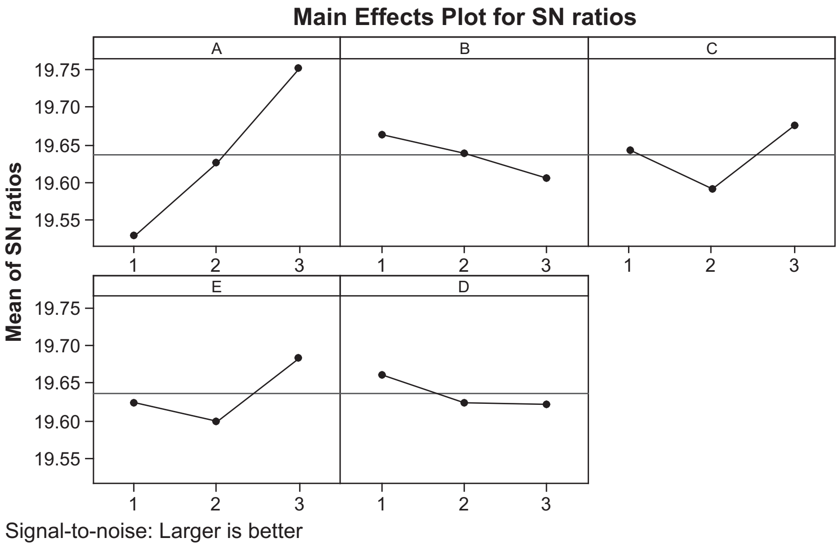

Fig. 4.2. Main factor effects on wire pull test.

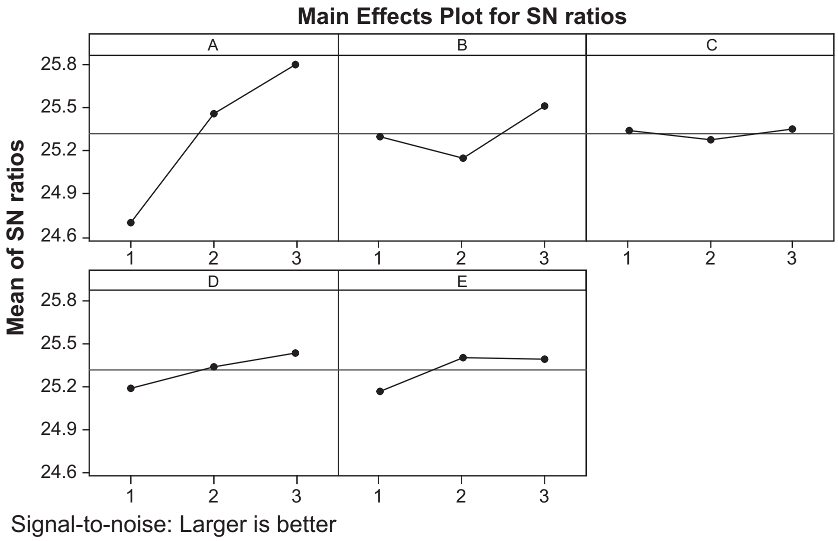

Fig. 4.3. Main factor effects on ball shear test.

Table 4.3
Analysis of variance for wire pull test.

Source	d.f.	SS	MS	*F*-value	Contribution (%)
A	2	0.149436	0.074718	12.03	54.76
B	2	0.00989*	–	–	–
C	2	0.021499	0.01075	1.73	4.23
D	2	0.006012*	–	–	–
E	2	0.022839	0.01142	1.84	4.76
Error	7	0.043483	0.006212		
(Pooled error)	11	0.059385	0.005399		36.25
Total	17	0.25316			100.00

Table 4.4
Analysis of variance for ball shear test.

Source	d.f.	SS	MS	*F*-value	Contribution (%)
A	2	3.82633	1.913165	20.43	69.47
B	2	0.38571	0.192855	2.06	4.33
C	2	0.02165*	–	–	–
D	2	0.18537*	–	–	–
E	2	0.20537	0.102685	1.10	0.91
Error	7	0.65726	0.093894		–
(Pooled error)	11	0.86428	0.078571		25.29
Total	17	5.2817			100.00

The expected mean value for the ball shear is

$$\begin{aligned}\hat{\eta} &= \bar{\eta} + (\bar{A}_3 - \bar{\eta}) + (\bar{B}_1 - \bar{\eta}) + (\bar{E}_3 - \bar{\eta}) \\ &= 25.80 + 25.30 + 25.39 - 2 \times 25.32 = 25.85db\end{aligned}$$

We conducted four times of confirmation experiments. According to the confirmation results, the average values of *SN* ratios for wire pull and ball shear were 19.77 and 25.55, respectively. These values were very close to the predicted values, suggesting that the choice of significant factors (i.e., Factors *A*, *C*, and *E*, as well as their relative levels) is appropriate.

Because the data located within the confirmation interval, onsite engineers implemented the optimum conditions in the wire bonding process.

4.2. Comparison of market value

At present, in the company, the monthly demand for the studied product is about 2 million, and it is predicted to increase to 10 million by the second season of 2011. According to production reports from the shop floor, the bonding yield of Cu wire is maintained at 99.3% for over three months after implementing the optimal conditions obtained by Taguchi methods. The annual direct cost savings is expected to exceed USD 1.08 million. In addition, the savings will reach over USD 10 million if Taguchi methods are applied in the manufacture of all of the company's products. Most importantly, with Cu wires, the company can provide products with better quality. One assembly manufacturer claimed that Cu wire capability and capacity has won 80% of the market share. Accordingly, it increases business revenues by 7.3% quarterly. The assembly manufacturer intends to use Cu wire bonding in 30% of its total capacity process and predicts that business revenues will double by the end of 2010.

5. Conclusions

Copper is an alternative materials for wire bonding. Switching from the use of Au to Cu is possible if the quality of Cu wire bonding process is controlled. In order to acquire high bonding yields and to maximize the benefits of operational revenues, IC assembly manufacturers aim for the introduction and efficient operational control of Cu wire bonding technology. Commonly, empirical or trial-and-error experiments are adopted in tuning Cu wire bonding parameters and in overcoming disqualifications in the bonding process during IC assembly. However, these strategies cannot simultaneously consider all of the parameters and their interactions. They cannot usually obtain the optimum parameter setting to maximize the wire bonding yield, leading to a loss of time and material resources. To our knowledge, the optimization of parameters for Cu wire bonding has not yet been addressed in literature. This study applied Taguchi methods to deal with this important issue. The superiority of our implementation was demonstrated in terms of Cu wire bonding yield, which increased from 98.5% to 99.3%, bringing about USD 0.7 million in savings. Results were corroborated by confirmatory trials. In the future, an intelligence-based approach, such as neural network and genetic algorithm, can be used to resolve this complicated parameter optimization problem.

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