Multi-response optimization of IC wire bonding for large probe marks by the RSM and desirability function approach

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Abstract
Wire bonding is key to high-quality IC assembly in semiconductor packaging. An electrical test was conducted before wire bonding. During the electrical test, the needle probes touched the surface of each bond pad resulting in a probe trace left, called probe marks. The probe mark on the bond pad affects the adhesion between the bond pad and copper ball. Generally, the bond ball can be removed easily under shear testing if the ratio of probe mark area to pad area is greater than 20%. A large probe mark causes a defect in the yield. However, rejecting the orders of wafer batches with large probe marks will result in a loss of market share and good relationships with clients. In order to find the optimal parameter settings for the batches of chips with probe mark areas larger than 20% and deal with multiple response problems, this study aims to optimize the parameters of operation for the IC with large probe marks in the wire bonding process to improve process capability and production yield. Response surface methodology (RSM) optimization with the desirability function approach was introduced into the central composite design to obtain the optimal process parameters efficiently and eliminate defects. The optimal parameter settings for the four factors were determined as follows: 90 mA bond power, 12 ms bond time, 10 g bond force, and 180 °C bond temperature. The validation testing confirms that optimal parameter settings increase yield from 98.84 to 99.94% with good process capability, helping companies improve quality, reduce defect costs, and improve customer relationships.

Keywords Wire bonding · Multi-response optimization · Response surface methodology · Desirability function · Probe mark · Shear force

1 Introduction
Wire bonding is key to high-quality IC assembly in semiconductor packaging. The main function of IC packaging is to provide the chip with electrical properties, protect the circuit, provide the original set function and durability, and conduct heat when the chip is working. The IC packaging process steps include wafer inspection, wafer back-grinding, wafer mount, die saw, die bond, oven, wire bonding, molding, marking, ball placement, singulation, final visual inspection, pack, and ship, as shown in Fig. 1. Among these, wire bonding is the most critical. Figure 2 shows pictures of (a) a copper ball of bonding and (b) the first bonding joint, second bonding joint, and wire arc.

For several decades, gold wire has been commonly used as the main material for wire bonding in IC packaging. However, the cost of gold has increased in recent years, and an increasing number of IC manufacturers are switching from gold (Au) to copper (Cu) to reduce material and production costs, making it challenging to find suitable parameters for bonding with copper wires. In addition, before IC wire bonding, an electrical test must be performed to ensure that the IC internal circuit is normal. During the electrical test, the needle probes touched the surface of each bond pad resulting in probe marks. In the bonding stage, the probe mark on the bond pad affects the adhesion between the bond pad and copper ball [1]. Less adhesion could cause the copper ball to be easily lifted off from the bond pad, leading to IC failure. Consequently, it affects the bond yield and the company’s revenue. According to industrial reports, an average 40% of yield loss during IC assembly can be attributed to improper control of copper wire bonding [2].
Hotchkiss et al. \[3\] conducted experiments and showed that the bond ball can be removed easily under shear testing if the ratio of probe mark area to pad area is greater than 20%. Normally, the more times the probe contacts the pad, the larger the probe mark. Figure 3 shows two different sizes of probe marks. The left probe mark with 20.38% area ratio was touched by probes four times causing a large probe mark. The right side was touched twice, causing 10.06% area ratio. The number of probe touches depends on the complexity of IC internal circuits and other requirements. Poh et al. \[4\] indicated that the aluminum pads with 1–3 times probe touching will have a loss of 0.53 to 0.56% in the yield of wire bonding. Yeoh et al. \[5\] indicated that a large and deep probe mark triggered intermetallic deterioration and bond degradation. Therefore, larger probe marks are likely to induce pad cracks during the bonding process \[6\].

A case IC packaging factory in Taiwan received a batch of wafers with a probe mark area ratio of approximately 20.38% and conducted a pilot wire bonding. The test results of the yields compared to smaller probe marks are shown in Table 1 and Fig. 4. This shows that the larger the probe mark, the lower the wire bond yield. Compared with 99.94% yield rate of 5.69% probe mark, the yield rate of 20.38% probe mark dropped to 98.84%, causing in 19 out of 1639 wire bonds failing due to copper ball detachment. With a 1.1% loss in yield rate, the monthly cost loss was approximately $6500 in US dollars.

In practice, the case IC packaging factory, according to the past experience, sets a threshold value of 20% of the probe mark area ratio that can accept orders for bonding. They generally reject the bonding of large probe marks over the threshold. However, IC package manufacturers often face a rejection or acceptance dilemma for batches of wafers with probe marks around 20%. According to the results of the pilot wire bonding mentioned above, a probe mark area ratio of 20.38% will cause a 1.1% defect rate, which is a huge loss. Thus, if the manufacturer accepts orders and is willing to conduct wire bonding, it will result in a significant loss of yield. However, if the manufacturer refuses to wire bonding, it will lose business and ruin relationships with clients. To gain better market share and maintain good relationships with clients, manufacturers are devoted to improving the bond yield of large probe marks. Consequently, by
summarizing the mentioned literature reviews as Table 2, the bonding for large probe mark has been a challenge and an important issue. The table also indicates the bonding limitations that this study aims to overcome. Thus, it is particularly important to optimize the bonding parameters for large probe mark sizes around the borderline.

Experimental design techniques such as the Taguchi method, response surface methodology (RSM), and factorial design have been widely used in process parameter optimization. Aggarwal et al. [7] pointed out that the significance of interactions and square terms of parameters are clearly predicted by RSM. The RSM technique can model the response based on significant parameters, their interactions, and the square terms. Thus, this method is a better tool for optimization than the Taguchi method. Most applications of Taguchi methods solve the single-response problem, with limited attention paid to multi-response problems [8]. When solving the multi-response problem, applying the traditional Taguchi method results in conflicts in the determination of the optimal parameter settings. That is, when finding the best combination of parameters that satisfy quality characteristic A, it may not be possible to satisfy quality characteristic B. In practice, engineers generally adjust the wire-bonding parameters using trial and error. To reduce manufacturing costs without losing quality, the copper wire bonding parameters must be systematically tuned to improve productivity and reduce quality loss. Papers [9, 10] proposed a procedure based on principal component analysis (PCA) to optimize the multi-response problems in the Taguchi method. However, when there are several principal components whose eigenvalues are greater than one, the choice of the best parameter settings by considering the trade-off among multiple responses is unclear. Liao [11] proposed a weighted PCA method that combines all principal components to form a multi-response performance index. Lin and Lin [12] employed the weighted PCA-based Taguchi method to determine the optimal parameter combination for using a silver alloy wire in the wire bonding process. To deal with multi-response problems, RSM is usually proposed and used with the desirability function (DF) approach. Multiple quality characteristics are converted into an optimization of the overall desirability [13]. Natarajan et al. [14] applied RSM combined with the desirability function for multiple response optimization in micro-end milling operation to achieve the maximum metal removal rate and minimum surface roughness. Tsai [15] converts multiple responses into a single synthetic performance index. A neural network model with a genetic algorithm method was then applied to determine the optimal parameter settings for the fine-pitch copper wire bonding process. They accompanied the results with those of the RSM integrated with the DF approach.

In order to find the optimal parameter settings for the batches of chips with probe mark areas larger than 20% and deal with multiple response problems, this study aims to optimize the parameters of operation for the large probe mark in the wire bonding process to improve process capability and production yield. RSM optimization with the desirability function approach was introduced into the central composite design (CCD) to obtain the optimal process parameters efficiently and eliminate defects.

The remainder of this paper is organized as follows. Section 2 describes the methodologies of RSM and DF for multi-response optimization. Section 3 describes the implementation of the experimental procedure. Section 4 presents the experimental results and obtains the optimal parameter settings. Verification experiments are also presented. Finally, the conclusions are presented in Section 5.

2 Methodologies

2.1 Response surface methodology

RSM uses mathematical and statistical procedures for the modeling and analysis of experimental results to search for significant process parameters and optimize the response [16]. RSM covers the response(s) of a process for a range of factor levels and further defines a region corresponding to the optimum solution or near-optimum solution. RSM saves cost and time in experiments by reducing the overall number of tests required. De Oliveira et al. [17] pointed out that RSM is a combination of the design of experiment, modeling techniques, and optimization models, by combining these three components in a stronger approach. The results of a process can be equated based on a small number of control parameters, and optimal responses can be guaranteed with minimum variance. Li et al. [18] pointed out that RSM combined with numerical simulation can efficiently obtain

| Table 2 | The bonding limitation to overcome in the study |
|---------|-----------------------------------------------|
| Complexity of IC internal circuits | General bonding | Intend to overcome | Reference cited |
| Number of probe touches | Common | High to overcome | [3] |
| Probe mark area | 1–3 | ≥ 4 | [4] |
| Yield loss | <20% | ≥ 20% | [3] |
| | 0.53–0.56% | 1.1% | Our pilot test |
optimal process parameters and eliminate defects in the product. RSM is commonly used for fitting first- or second-order polynomial equations for the response based on these factors. The qualitative relationship between the response and factors is presented as follows [19].

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \]  

(1)

where \( Y \) is the response, \( \beta_0 \) is the constant term of the model, \( \beta_i \) is the coefficient of the linear terms, \( \beta_{ij} \) is the coefficient of the quadratic terms, \( \beta_{ij} \) is the coefficient of the interaction terms, and \( \epsilon \) is the residual.

In addition, several standard second-order RSM designs have been proposed. The central composite design (CCD) is one of the most widely used designs [17]. CCD consists of three point types: (1) factorial points, (2) a central point, and (3) axial points, which are at distance \( a \) from the central point. CCD is appropriate for sequential experimentation and provides a reasonable amount of information for testing the lack-of-fit without involving an unusually large number of experimental runs. In addition, CCD is appropriate for studying factors with three and/or five levels. The experimental runs in CCD were estimated by [19].

\[ N = 2^k + 2k + C_p \]  

(2)

where \( k \) is the number of independent variables and \( C_p \) is the replicate number of the central point.

Four factors \( (k = 4) \) were applied in this study. In addition, 26 experimental runs were considered, including two central points on the bond ball.

### 2.2 The desirability function

In the wire-bonding process, several responses must be optimized simultaneously. RSM is usually integrated with a desirability function (DF) to transform multiple quality characteristics into a single desirability function, which can be optimized using univariate techniques [20]. In this approach, each response \( Y_i \) is first converted into an individual desirability function \( d_i \) ranging from 0 to 1 \((0 \leq d_i \leq 1)\). \( d(Y) = 0 \) represents a completely undesirable value of \( Y \), whereas \( d(Y) = 1 \) indicates a completely desirable or ideal response value. The individual desirability functions are then combined as an overall desirability \( D \) using the geometric mean as follows:

\[ D = (d_1 \times d_2 \times d_3 \times \cdots \times d_i)^{\frac{1}{k}} \quad 0 \leq D \leq 1 \]  

(3)

where \( k \) denotes the number of responses. \( D \) is the result of a combination of multi-quality characteristics, and its value represents the degree of closeness to the ideal state. Its value is also between 0 and 1, and the closer the value is to 1, the more it is in line with the ideal response value. The largest \( D \) value was used to determine the optimized parameters. This study had five quality characteristics (responses). Among these responses, the ball shear force and intermetallic compound (IMC) have a “larger-the-better” attribute, the ball size and ball thickness have a “nominal-the-better” attribute, and Al splash has a “smaller-the-better” attribute. Depending on whether a particular \( Y_i \) is to be maximized, minimized, or assigned to a target value, different desirability functions \( d \) \((Y_i)\) can be described by the following equation:

- **Larger-the-better (LTB)**

\[ d_i = \begin{cases} 
0 & \text{if } \hat{Y}_i < L_i \\
\left[ \frac{\hat{Y}_i - L_i}{U_i - L_i} \right]^s & \text{if } L_i \leq \hat{Y}_i \leq T_i, s \geq 0 \\
1 & \text{if } \hat{Y}_i > T_i 
\end{cases} \]  

(4)

- **Smaller-the-better (STB)**

\[ d_i = \begin{cases} 
1 & \text{if } \hat{Y}_i < T_i \\
\left[ \frac{U_i - \hat{Y}_i}{U_i - T_i} \right]^t & \text{if } T_i \leq \hat{Y}_i \leq U_i, t \geq 0 \\
0 & \text{if } \hat{Y}_i > U_i 
\end{cases} \]  

(5)

- **Nominal-the-better (NTB)**

\[ d_i = \begin{cases} 
0 & \text{if } \hat{Y}_i < L_i \\
\left[ \frac{\hat{Y}_i - L_i}{T_i - L_i} \right]^s & \text{if } L_i \leq \hat{Y}_i \leq T_i, s \geq 0 \\
\left[ \frac{U_i - \hat{Y}_i}{U_i - T_i} \right]^t & \text{if } T_i \leq \hat{Y}_i \leq U_i, t \geq 0 \\
0 & \text{if } \hat{Y}_i > U_i 
\end{cases} \]  

(6)

where \( T_i \) is the target value, \( U_i \) is the upper limit of \( Y_i \), and \( L_i \) is the lower limit of \( Y_i \). \( s \) and \( t \) are the weights. When the weight value is one, the desirability function is linear [21]. Therefore, the weight was set to one in this study.

### 3 Experimental procedure

In this study, the material and bonding machine configurations were set according to the bond pad dimensions and wire diameter, as shown in Table 3. Figure 5 illustrates the bonding machine parameters as input factors to increase the bonding yield in the study. According to the literature on parameter optimization for the bonding process for IC assembly and the expert knowledge of engineers, four adjustable factors were considered influential in improving the bonding quality in this study [2, 12, 15, 22]. These four control factors are bond power (A), bond time (B), bond force (C), and bond temperature (D), as shown in Table 4. Other factors, such as the tip height of the wire bonding
capillary and the contact velocity, are already determined by the diameter of the copper wire; therefore, they are considered to be fixed.

After wire bonding, five quality characteristics (responses) were collected to verify the quality of wire bonding. These responses are the ball shear force, ball size, ball thickness, aluminum splash (AS), and intermetallic compound (IMC). The ball shear force is a measurement of the bond adhesive strength using a destructive test, as shown in Fig. 6, in which a shear tool is applied in the lateral direction until the ball separates from the pad. The measured peak force causing the separation was the ball shear force (in grams) [23–25]. The ball size and thickness are the diameter and height of the bond ball, respectively, as shown in Fig. 7. The AS is the aluminum splashed out of the copper ball interface due to the bonding squeeze, as shown in Fig. 7. The AS diameter should

| Table 3 Bonding machine configurations |
|----------------------------------------|
| Bonder series | K&S ICONN PROCU |
| Package type | LFBGA |
| Bond pad open (BPO) | 44.1 µm |
| Bond pad pitch (BPP) | 50.4 µm |
| Al thickness | 2.8 µm |
| Wafer technology | 28 nm |
| Wire type | AgPdCu |
| Wire diameters | 17.5 µm |

| Table 4 Control factors and factor levels |
|------------------------------------------|
| Factors | Unit | Levels |
| A: Bond power | mA | 55 80 105 |
| B: Bond time | ms | 5 15 25 |
| C: Bond force | g | 5 10 15 |
| D: Bond temperature | °C | 155 175 195 |

| Table 5 Attributes and specifications of each quality characteristics |
|---------------------------------------------------------------|
| Responses | Attributes | Specification |
| Ball shear force | Larger-the-better (LTB) | ≥ 8 g |
| Ball size | Nominal-the-better (NTB) | 30.8 – 39.6 µm |
| Ball thickness | Nominal-the-better (NTB) | 8 – 12 µm |
| AS | Smaller-the-better (STB) | ≤ 44.1 µm |
| IMC | Larger-the-better (LTB) | ≥ 80 % |
Table 6  CCD design and responses

| Run | Code values | A  | B  | C  | D  | Shear force | Ball size | Ball thickness | AS  | IMC % |
|-----|-------------|----|----|----|----|-------------|-----------|----------------|-----|-------|
| #1  | ---+        | 55 | 5  | 5  | 195| 10.55       | 31.98     | 11.11          | 34.87| 94.36 |
| #2  | 00-0        | 80 | 15 | 5  | 175| 10.96       | 35.16     | 9.16           | 37.7 | 93.08 |
| #3  | + ++        | 105| 25 | 5  | 195| 13.54       | 36.5      | 10.59          | 40.78| 96.66 |
| #4  | 0 + 00      | 80 | 25 | 15 | 175| 16.96       | 35.84     | 9.11           | 37.76| 95.61 |
| #5  | + --        | 55 | 5  | 15 | 195| 14.18       | 32.89     | 10.97          | 33.86| 94.58 |
| #6  | ++ + +      | 105| 25 | 5  | 195| 13.99       | 32.08     | 9.19           | 40.87| 96.25 |
| #7  | + +++       | 105| 25 | 5  | 195| 19.24       | 38.45     | 8.1            | 42.14| 97.49 |
| #8  | + ++        | 55 | 25 | 5  | 195| 13.54       | 36.5      | 9.02           | 37.97| 95.5  |
| #9  | + + ++      | 105| 5  | 5  | 195| 11.53       | 33.96     | 10.86          | 35.93| 95.88 |
| #10 | + + +       | 55 | 25 | 5  | 195| 16.41       | 36.13     | 9.28           | 38.02| 95.17 |
| #11 | 000-        | 80 | 15 | 10 | 155| 13.85       | 33.75     | 10.61          | 36.92| 94.3  |
| #12 | + + -       | 105| 5  | 15 | 155| 14.27       | 35.43     | 9.35           | 37.43| 94.04 |
| #13 | 0000        | 80 | 15 | 10 | 155| 15.05       | 35.04     | 9.89           | 38.11| 95.9  |
| #14 | - - - -     | 55 | 5  | 5  | 155| 10.26       | 31.58     | 11.6           | 34.14| 93.06 |
| #15 | -- + +      | 55 | 5  | 15 | 195| 14.83       | 34.21     | 9.34           | 36.78| 95.86 |
| #16 | + ---       | 105| 5  | 5  | 155| 10.55       | 36.19     | 9.25           | 38.81| 93.74 |
| #17 | + + + +     | 55 | 25 | 5  | 155| 13.96       | 35.22     | 9.58           | 37.52| 94.62 |
| #18 | + + + -     | 105| 25 | 5  | 155| 18.77       | 37.65     | 8.24           | 41.53| 95.62 |
| #19 | 0-0-0       | 80 | 5  | 10 | 175| 12.26       | 32.89     | 11.6           | 35.66| 94.05 |
| #20 | 00 + 0      | 80 | 15 | 15 | 175| 18.13       | 32.43     | 10.89          | 36.14| 94.05 |
| #21 | - + + +     | 55 | 25 | 15 | 195| 17.85       | 34.57     | 9.39           | 37.37| 95.67 |
| #22 | + + + 0     | 105| 15 | 10 | 175| 14.26       | 38.95     | 8.34           | 41.53| 95.32 |
| #23 | + + + +     | 105| 5  | 15 | 195| 15.33       | 35.21     | 9.87           | 38.33| 96.2  |
| #24 | 0000        | 80 | 15 | 10 | 175| 14.94       | 34.98     | 10.01          | 38.17| 95.78 |
| #25 | -000       | 55 | 15 | 10 | 175| 14.53       | 32.17     | 11.25          | 34.82| 93.88 |
| #26 | 000 +       | 80 | 15 | 10 | 195| 15.25       | 36.12     | 8.69           | 38.33| 96.49 |

Table 7  Coefficients of the regression model for the response variables

| Term  | Coefficients | Ball size | AS | IMC % |
|-------|--------------|-----------|----|-------|
|       | Shear force  | Ball thickness |     |       |
| Constant | 16.087  | 35.346   | 10.02 | 38.295 | 94.957 |
| A      | 2.736*     | 1.514*   | -0.482* | 1.722* | 0.972* |
| B      | 1.868*     | 1.807*   | -0.688* | 1.786* | 0.546* |
| C      | 0.636*     | 0.819*   | -0.228 | 0.705* | 0.655* |
| D      | 0.031      | 0.361    | -0.002 | 0.134  | 0.874* |
| A^2    | -0.397     | 0.102    | -0.249 | -0.172 | -0.063 |
| B^2    | 0.318      | 0.907    | 0.311  | 0.863  | 0.167  |
| C^2    | 0.253      | 0.337    | -0.019 | 0.573  | -1.098*|
| D^2    | -0.742     | -0.523   | -0.394 | -0.718 | 0.732  |
| AB     | 0.424*     | -0.237   | 0.092  | 0.037  | 0.254  |
| AC     | -0.087     | -0.233   | -0.064 | -0.176 | -0.416*|
| AD     | -0.064     | 0.088    | 0.431  | -0.119 | -0.024 |
| BC     | -0.073     | -0.162   | 0.056  | -0.191 | -0.279 |
| BD     | -0.051     | 0.099    | 0.108  | -0.022 | -0.014 |
| CD     | 0.103      | -0.144   | -0.246 | -0.007 | 0.051  |
| R^2 (%)| 98.05      | 86.39    | 64.48  | 88.88  | 89.7   |
| Adjusted R^2 (%)| 98.57 | 69.08 | 21.54 | 74.27 | 79.6  |

*p value < 0.05
not exceed the pad width. IMC is a newly formed layer of alloy compounds between the ball and pad during bonding, as shown in Fig. 8. The IMC produced a strong adhesion to fix the copper ball on the aluminum pad. However, in each ball circle, areas that do not produce the alloy compound are called non-IMC areas. According to experience, the IMC area needs to be greater than 80% of the ball circle area to ensure the bonding strength [26]. The specifications and attributes of the five responses are shown in Table 5.

### 4 Results and data analysis

#### 4.1 Experimental results and overall desirability function

In this study, the CCD experimental design was used, and the results of the 26 trials are shown in Table 6. Minitab 21 software was used for the analysis. The RSM equations for each response are presented in Table 7. $R^2$ indicates the percentage of contribution of each model term. The $R^2$ for shear force, ball size, AS, and IMC% responses were all above 80%, indicating a good fit of models. The corresponding

| Exp. run | $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $D$ |
|----------|-------|-------|-------|-------|-------|-----|
| #1       | 0.294 | 0.152 | 0.180 | 1.000 | 0.749 | 0.3598 |
| #2       | 0.331 | 0.231 | 0.400 | 1.000 | 0.837 | 0.4805 |
| #3       | 0.543 | 0.604 | 0.495 | 1.000 | 0.987 | 0.6934 |
| #4       | 0.628 | 0.667 | 0.754 | 1.000 | 1.000 | 0.7939 |
| #5       | 0.589 | 0.268 | 0.337 | 1.000 | 0.939 | 0.5492 |
| #6       | 0.737 | 0.863 | 0.574 | 0.945 | 0.981 | 0.8052 |
| #7       | 0.774 | 0.864 | 0.889 | 1.000 | 0.854 | 0.8733 |
| #8       | 0.833 | 0.918 | 0.720 | 0.936 | 0.891 | 0.8560 |
| #9       | 0.890 | 0.671 | 0.782 | 0.872 | 1.000 | 0.8355 |
| #10      | 0.813 | 0.604 | 0.180 | 1.000 | 0.951 | 0.6095 |
| #11      | 1.000 | 0.461 | 0.653 | 1.000 | 0.885 | 0.7676 |
| #12      | 1.000 | 0.577 | 0.625 | 1.000 | 0.968 | 0.8102 |
| #13      | 1.000 | 0.817 | 0.895 | 1.000 | 1.000 | 0.9394 |
| #14      | 0.916 | 0.829 | 0.949 | 1.000 | 1.000 | 0.9367 |
| #15      | 0.942 | 0.946 | 0.388 | 1.000 | 1.000 | 0.8087 |
| #16      | 1.000 | 0.318 | 0.499 | 0.545 | 0.951 | 0.6069 |
| #17      | 1.000 | 0.207 | 0.624 | 0.431 | 1.000 | 0.5611 |
| #18      | 1.000 | 0.861 | 0.759 | 1.000 | 0.950 | 0.9093 |
| #19      | 1.000 | 0.921 | 0.958 | 0.879 | 1.000 | 0.9506 |
| #20      | 0.981 | 0.858 | 0.703 | 0.975 | 0.930 | 0.8830 |
| #21      | 0.979 | 0.989 | 0.513 | 1.000 | 1.000 | 0.8693 |
| #22      | 1.000 | 0.177 | 0.191 | 0.474 | 1.000 | 0.4373 |
| #23      | 1.000 | 0.027 | 0.634 | 0.427 | 1.000 | 0.3745 |
| #24      | 1.000 | 0.530 | 0.135 | 0.474 | 1.000 | 0.5081 |
| #25      | 1.000 | 0.041 | 0.056 | 0.361 | 1.000 | 0.2419 |
| #26      | 1.000 | 0.141 | 0.107 | 0.227 | 1.000 | 0.3213 |

| Term     | Coefficient | SE coefficient | t value | p value |
|----------|-------------|----------------|---------|---------|
| Constant | 0.7298      | 0.0471         | 15.48   | <0.0001 |
| A        | -0.0418     | 0.0280         | -1.49   | 0.164   |
| B        | -0.0651     | 0.0280         | -2.32   | 0.040*  |
| C        | 0.0160      | 0.0280         | 0.57    | 0.580   |
| D        | -0.0030     | 0.0280         | -0.11   | 0.916   |
| A²       | -0.1671     | 0.0743         | -2.25   | 0.046*  |
| B²       | -0.0751     | 0.0743         | -1.01   | 0.334   |
| C²       | 0.0269      | 0.0743         | 0.36    | 0.724   |
| D²       | 0.1490      | 0.0743         | 2.01    | 0.070   |
| AB       | -0.2005     | 0.0297         | -6.75   | <0.0001*|
| AC       | -0.0545     | 0.0297         | -1.83   | 0.094   |
| AD       | -0.0199     | 0.0297         | -0.67   | 0.518   |
| BC       | -0.0663     | 0.0297         | -2.23   | 0.047*  |
| BD       | -0.0344     | 0.0297         | -1.16   | 0.272   |
| CD       | 0.0085      | 0.0297         | 0.29    | 0.779   |

$s = 0.11892; \ R - sq = 86.87%; \ R - sq(adj) = 70.15%$

*p value < 0.05*
The RSM was then conducted using SPCI, D, as the dependent variable, and four factors as independent variables. The second-order quadratic model was developed as shown in Eq. (7).

$D = 0.7298 - 0.0418A - 0.0651B + 0.0160C - 0.0030D - 0.1671A^2 - 0.0751B^2 + 0.0269C^2 + 0.1490D^2 - 0.2005AB - 0.0545AC - 0.0199AD - 0.0663BC - 0.0344BD + 0.0085CD$

The $R^2$ of the fitted regression model was 86.87% and the adjusted $R^2$ was 70.15% (Table 10). The ANOVA results for the single desirability function $D$ are presented in Table 10. Figure 9 shows the response surface plot of the composite desirability function (SCPI). By using the JMP statistical software, we can obtain the prediction profiler chart according to the measured responses, as shown in Fig. 10. Consequently, the optimal parameters can be obtained as a bond power (or oscillation current) of 90 mA, bond time of 12 ms, bond pressure of 10 g, and bond temperature of 180 °C, as listed in Table 11.

### 4.3 Confirmation experiments and comparison of the optimization performance

Experiments were conducted to verify whether the optimal parameter settings by the optimization methods improved
the quality of copper wire bonding. Confirmation experiments are performed by testing the optimal levels of the control factors suggested by the proposed DF-RSM method. Each experiment was performed in triplicate. The confirmation results with the process capability (Cpk) for each response and yield rate were evaluated according to the optimal parameter settings. All the inspection items are within the specification requirements, and the process capabilities are greater than 1.67 which indicates excellent process capability [27], as shown in Table 12.

Furthermore, from the optical microscope images shown in Fig. 11, the area of the IMC was more than 80% (Table 5). Improper bonding parameters can cause bond pad cracking, so a crater test is used to check for pad cracking by etching the pad and exposing its metal layer. The image in Fig. 11 showed no cracks in the pond pad. Finally, the cross-section of the copper ball confirmed that there was no abnormal appearance and that the circuit under the bond pad was not broken. Therefore, the set of optimal parameters determined is suitable for bonding.

| Bond power | Bond time | Bond force | Bond Temp |
|------------|-----------|------------|-----------|
| 90 mA      | 12 ms     | 10 g       | 180 °C    |
Additionally, the determined optimal parameters were tested for ICs with probe marks of different sizes to understand how much yield could be improved by actual wire bonding. According to the experimental results as shown in Table 13, it is found that the bond yield rate can reach 99.94% at 20.38% area ratio of the probe marks, which is improved from 98.84%. In addition, the bond yield can even reached 100% at 5.69% area ratio of the probe marks. The improvement results were significant, as shown in Fig. 12.

### Table 12 Verification results of the determined optimal parameters

| Verify items       | Bond quantity | Requirement | Verification results | Quality |
|--------------------|---------------|-------------|----------------------|---------|
|                    |               |             | Max  | Min  | Avg. | Std. | Cpk  |         |
| Ball shear(g)      | 16 wire / 3pcs| > 8.0 g     | 16.35 | 14.55 | 15.51 | 0.46 | 5.44 | Pass    |
| Ball size(um)      | 4 ball / 3pcs | 30~39.6um   | 36.6 | 36.2 | 36.4 | 0.19 | 9.82 | Pass    |
| Ball thickness(um) | 4 ball / 3pcs | 10±2 um     | 10.45 | 10.32 | 10.37 | 0.13 | 6.08 | Pass    |
| AS (um)            | 4 ball / 3pcs | < 44.1um    | 40.3 | 38.1 | 39.33 | –   | –    | Pass    |
| IMC (%)            | 4 ball / 3pcs | > 80%       | 94.99% | 90.34% | 92.42% | –   | –    | Pass    |
| Cratering          | 3pcs          | No crack    | 0/3   |      |      |      |      | Pass    |
| Bond yield         | 50pcs         | > 99%       | 100%  |      |      |      |      | Pass    |

![IMC and Cratering test images](image)

**Fig. 11** Optical microscope images of bonding results of the optimal parameters

| Table 13 Verification of bond yield improvement |
|-----------------------------------------------|
| **Probe mark ratio** | **Bond pad** | **Bond quantity** | **Ball failed quantity** | **Bond yield** |
| 5.69% (touch once)   | -              | 1750            | 0                      | 100.00%       |
| 10.06% (touch twice) | -              | 1749            | 1                      | 99.94%        |
| 14.86% (triple touch)| -              | 1737            | 1                      | 99.94%        |
| 20.38% (four touch)  | -              | 1738            | 1                      | 99.94%        |

![Bond yield comparison chart](image)

**Fig. 12** Comparison of original and proposed optimal parameter bond yield

### 5 Conclusions

It is important to optimize the parameter settings for the wire bonding of large probe mark sizes around the borderline. To solve the multi-objective optimization problem, the DF-RSM method was proposed to derive the optimal parameter settings for the wire bonding of large probe marks. We selected four factors and five quality measures to optimize the wire bonding process with multiple quality characteristics. The optimal parameter settings for the four factors were determined: 90 mA bond power, 12 ms bond time, 10 g bond force, and 180 °C bond temperature. Validation testing confirmed that optimal parameter settings resulted in qualified wire bonding quality because all inspection chips met the specifications and reached a high yield rate.

The chips with different probe mark ratios were also bonded for tests using the obtained optimal parameters, and it was found that all the yields of different probe marks have been improved, especially for a probe mark area of 20.38%. Its yield rate increased from 98.84 to 99.94%, which was quite significant. Improving the yield rate of the bonding of large probe marks means that the number of machine downtimes can be reduced, the production line capacity can be increased, and the client’s orders might increase. In the future, different multi-objective optimization methods can be proposed for further comparisons. In addition, modeling techniques of artificial networks with heuristic algorithms can be considered for parameter optimization.
Appendix. ANOVA results for each response

Table 14 ANOVA for shear force

| Source of variance | df | SS     | MS     | F value | p value |
|--------------------|----|--------|--------|---------|---------|
| A                  | 1  | 134.699| 134.699| 353.03  | <0.0001*|
| B                  | 1  | 62.832 | 62.832 | 164.68  | <0.0001*|
| C                  | 1  | 7.271  | 7.271  | 19.06   | 0.001*  |
| D                  | 1  | 0.017  | 0.017  | 0.04    | 0.838   |
| A²                 | 1  | 0.403  | 0.403  | 1.06    | 0.326   |
| B²                 | 1  | 0.260  | 0.260  | 0.68    | 0.427   |
| C²                 | 1  | 0.164  | 0.164  | 0.43    | 0.525   |
| D²                 | 1  | 1.408  | 1.408  | 3.69    | 0.081   |
| AB                 | 1  | 2.882  | 2.882  | 7.55    | 0.019*  |
| AC                 | 1  | 0.121  | 0.121  | 0.32    | 0.585   |
| AD                 | 1  | 0.066  | 0.066  | 0.17    | 0.685   |
| BC                 | 1  | 0.086  | 0.086  | 0.22    | 0.645   |
| BD                 | 1  | 0.041  | 0.041  | 0.11    | 0.749   |
| CD                 | 1  | 0.170  | 0.170  | 0.45    | 0.518   |
| Error              | 11 | 4.197  | 0.382  |         |         |
| Total              | 25 | 4.197  | 0.382  |         |         |

*p value < 0.05

Table 15 ANOVA for ball size

| Source of variance | df | SS     | MS     | F value | p value |
|--------------------|----|--------|--------|---------|---------|
| A                  | 1  | 41.253 | 41.253 | 23.61   | 0.001*  |
| B                  | 1  | 58.753 | 58.753 | 33.62   | <0.0001*|
| C                  | 1  | 12.070 | 12.070 | 6.91    | 0.023   |
| D                  | 1  | 2.347  | 2.347  | 1.34    | 0.271   |
| A²                 | 1  | 0.027  | 0.027  | 0.02    | 0.904   |
| B²                 | 1  | 2.106  | 2.106  | 1.21    | 0.296   |
| C²                 | 1  | 0.291  | 0.2905 | 0.17    | 0.691   |
| D²                 | 1  | 0.701  | 0.701  | 0.40    | 0.539   |
| AB                 | 1  | 0.898  | 0.8978 | 0.51    | 0.488   |
| AC                 | 1  | 0.870  | 0.8696 | 0.50    | 0.495   |
| AD                 | 1  | 0.124  | 0.1243 | 0.07    | 0.795   |
| BC                 | 1  | 0.419  | 0.4193 | 0.24    | 0.634   |
| BD                 | 1  | 0.158  | 0.1580 | 0.09    | 0.769   |
| CD                 | 1  | 0.334  | 0.3335 | 0.19    | 0.671   |
| Error              | 11 | 19.222 | 1.7474 |         |         |
| Total              | 25 | 19.222 | 1.7474 |         |         |

*p value < 0.05

Table 16 ANOVA for ball thickness

| Source of variance | df | SS     | MS     | F value | p value |
|--------------------|----|--------|--------|---------|---------|
| A                  | 1  | 4.1857 | 4.1856 | 4.58    | 0.056   |
| B                  | 1  | 8.5147 | 8.5146 | 9.32    | 0.011*  |
| C                  | 1  | 0.9339 | 0.9338 | 1.02    | 0.334   |
| D                  | 1  | 0.0000 | 0.0000 | 0.00    | 0.994   |
| A²                 | 1  | 0.1587 | 0.1586 | 0.17    | 0.685   |
| B²                 | 1  | 0.2479 | 0.2478 | 0.27    | 0.613   |
| C²                 | 1  | 0.0009 | 0.0009 | 0.00    | 0.975   |
| D²                 | 1  | 0.3974 | 0.3973 | 0.43    | 0.523   |
| AB                 | 1  | 0.1351 | 0.1350 | 0.15    | 0.708   |
| AC                 | 1  | 0.0663 | 0.0663 | 0.07    | 0.793   |
| AD                 | 1  | 2.9670 | 2.9670 | 3.25    | 0.099   |
| BC                 | 1  | 0.0495 | 0.0495 | 0.05    | 0.820   |
| BD                 | 1  | 0.1871 | 0.1870 | 0.20    | 0.660   |
| CD                 | 1  | 0.9653 | 0.9653 | 1.06    | 0.326   |
| Error              | 11 | 10.0536| 0.9139 |         |         |
| Total              | 25 | 10.0536| 0.9139 |         |         |

*p value < 0.05

Table 17 ANOVA for AS

| Source of variance | df | SS     | MS     | F value | p value |
|--------------------|----|--------|--------|---------|---------|
| A                  | 1  | 53.389 | 53.389 | 37.33   | <0.0001*|
| B                  | 1  | 57.423 | 57.423 | 40.15   | <0.0001*|
| C                  | 1  | 8.9465 | 8.9465 | 6.26    | 0.029*  |
| D                  | 1  | 0.322  | 0.3219 | 0.23    | 0.644   |
| A²                 | 1  | 0.076  | 0.0757 | 0.05    | 0.822   |
| B²                 | 1  | 1.907  | 1.9075 | 1.33    | 0.273   |
| C²                 | 1  | 0.2841 | 0.284 | 0.59    | 0.459   |
| D²                 | 1  | 1.322  | 1.3220 | 0.92    | 0.357   |
| AB                 | 1  | 0.022  | 0.0218 | 0.02    | 0.904   |
| AC                 | 1  | 0.494  | 0.4935 | 0.35    | 0.569   |
| AD                 | 1  | 0.289  | 0.2880 | 0.16    | 0.697   |
| BC                 | 1  | 0.581  | 0.5814 | 0.41    | 0.537   |
| BD                 | 1  | 0.008  | 0.0077 | 0.01    | 0.943   |
| CD                 | 1  | 0.001  | 0.0008 | 0.00    | 0.982   |
| Error              | 11 | 15.731 | 1.4301 |         |         |
| Total              | 25 | 15.731 | 1.4301 |         |         |

*p value < 0.05
Table 18 ANOVA for IMC

| Source of variance | df | SS   | MS   | F value | p value |
|--------------------|----|------|------|---------|---------|
| A                  | 1  | 17.0139 | 17.0139 | 30.92 | <0.0001* |
| B                  | 1  | 5.3574 | 5.3574 | 9.74 | 0.010*    |
| C                  | 1  | 7.7224 | 7.7224 | 14.03 | 0.003*    |
| D                  | 1  | 13.7463 | 13.7463 | 24.98 | <0.0001* |
| A²                 | 1  | 0.0102 | 0.0102 | 0.02 | 0.894     |
| B²                 | 1  | 0.0712 | 0.0712 | 0.13 | 0.726     |
| C²                 | 1  | 3.0889 | 3.0889 | 5.61 | 0.037*    |
| D²                 | 1  | 1.3713 | 1.3713 | 2.49 | 0.143     |
| AB                 | 1  | 1.0302 | 1.0302 | 1.87 | 0.199     |
| AC                 | 1  | 2.7722 | 2.7722 | 5.04 | 0.046*    |
| AD                 | 1  | 0.0090 | 0.0090 | 0.02 | 0.900     |
| BC                 | 1  | 1.2432 | 1.2432 | 2.26 | 0.161     |
| BD                 | 1  | 0.0030 | 0.0030 | 0.01 | 0.942     |
| CD                 | 1  | 0.0420 | 0.0420 | 0.08 | 0.787     |
| Error              | 11 | 6.0534 | 0.5503 |       |          |
| Total              | 25 | 58.7846 |        |       |          |

*p value < 0.05

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Declarations

Consent to participate N/A

Consent for publication N/A

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