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An Application of a Hybrid Method to Eliminate Adhesion Problems in Wirebonding Through Increased Bond Temperature

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ABSTRACT

One of the major problems in wirebonding process is the creation of intimate welding between the gold wire and the aluminized bond pads. This paper presents a way of circumventing this problem through the application of a hybrid of response surface analysis and Taguchi method. Results show that increasing temperature from 220°C to 240°C and utilizing an optimized bond setting (Time = 20ms, Power = 87mW, and Force = 65g) will result in higher ball shear test results, an indicator of good adhesion. It is also demonstrated that bond features such as ball height, ball diameter, ball area, outweld area, as well as intermetallic growth are better under these settings. The derived setting was verified in a confirmatory run and implemented on a customer. Performance of the process showed improved levels of ppm defects.

1. Introduction

Most of the problems plaguing wirebonding of integrated circuits (ICs) can be traced to adhesion problems. An example of which is the problem caused by intermetallic growth which occurs when gold (Au) wires are bonded to aluminum (Al) bond contacts. Intermetallic growth is the welding connecting the gold and aluminum and is mainly responsible for the adhesion strength of ball bonds through the use of heat. However, Kohl, et al. (1988) noted that excessive heat (usually greater than 300°C) can result to excessive $AuAl_2$ intermetallic (known as Kirkedall voiding). This can result to reliability failure of Au and Al bond contacts. The same study showed that the welding can be destroyed by longer periods of heat exposure. The typical industry standard for bonding temperature is placed between 200°C to 300°C.

Bonding pad metallization composition is another factor that must be considered. The most common types of bonding pad metallization compositions consist of pure Al, combination of Al and silicon (Si), and Al-Si and/or copper (Cu) combinations. Pure Al is the softest, while Al-Si-Cu is the hardest. Cu is usually added to enhance resistance of the conductor metal against electromigration or the movement/displacement of conductor metal ions due to the passage of electrical current. One disadvantage of this combination, as observed by Thomas, et. al. (1984), is the effect on ball bond lifting due to the formation of micro-corrosion due to Al.[1]

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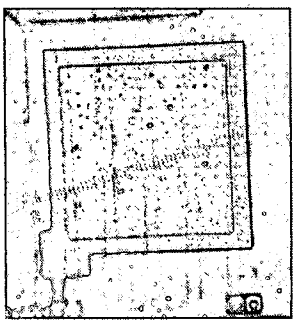
Figure 1. Metallographic cross section of Au bond on Al exposed to 330C/5hrs (after Kohl). The diffusion zone, $AuAl_2$ intermetallic formation, grows with increasing anneal time until practically the whole ball is consumed. Continuous growth of pores can result to brittleness and breakage of the Au-Al contact at thermal stress.

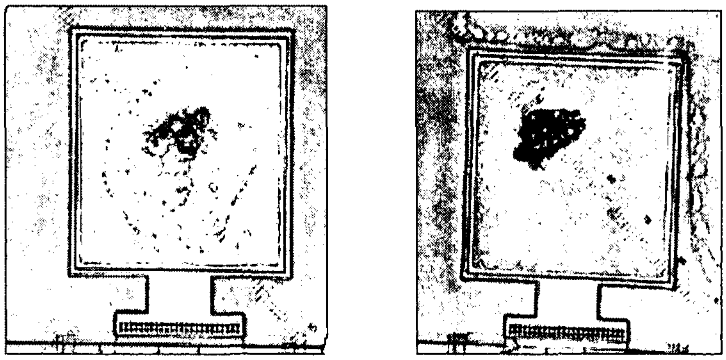
Another cause of adhesion failure is the incomplete etching of the bonding pads due to over-firing of thick film layer during wafer fabrication. This is commonly known as 'residual glass on pad'. The presence of glass violates the basic welding parameters which makes bonding of wires to the bond pad surface difficult. Glassivated bond pads are usually seen with undamaged bonding pads even after several capillary impression marks are made during wirebonding process. Figures 2 and 3 describe how the said defect can be easily identified through the use of KOH and NaOH solution.

(a) Before



(b) After

Figure 2. Glassivated Bond Pad before and after etch test. *Glassivation is identified if after submerging unit to solution, the bond pad metallizations were not completely etched after a NaOH etch test.*



(a) Before (b)After

Figure 3. Unglassivated Bond Pad Before and After etch test. *A non-wafer fab-related lifted ball bond can be identified very easily if the bond pad metallizations are completely etched out after a NaOH test.*

The geometry of the capillary is another important factor that must be considered as it affects ball bond formations. The ball size and height is influenced by the cone diameter (CD), the chamfer angle (CA), the face angle (FA) and the capillary tip (F). The most common CA varies form 90° to 120°. A 90° CA is designed for bonding surfaces with good bondability. Lifted ball bonds may also occur if a capillary with damaged tip or a capillary with higher CA value is used. This is one of the primary reasons why capillary manufacturers even developed a capillary with two chamfer angles to improve both the ball bond and the stitch weld.

Figure 4. Photo of a capillary. *Capillaries are usually made of Ruby, Ceramic, or Sapphire.*

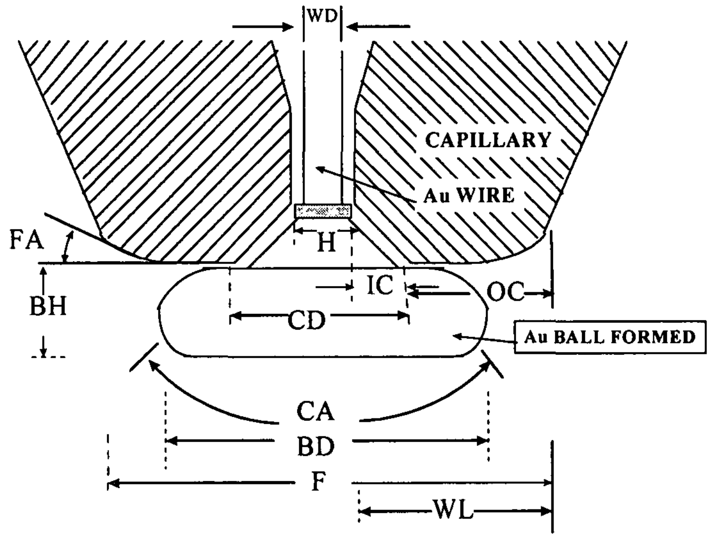


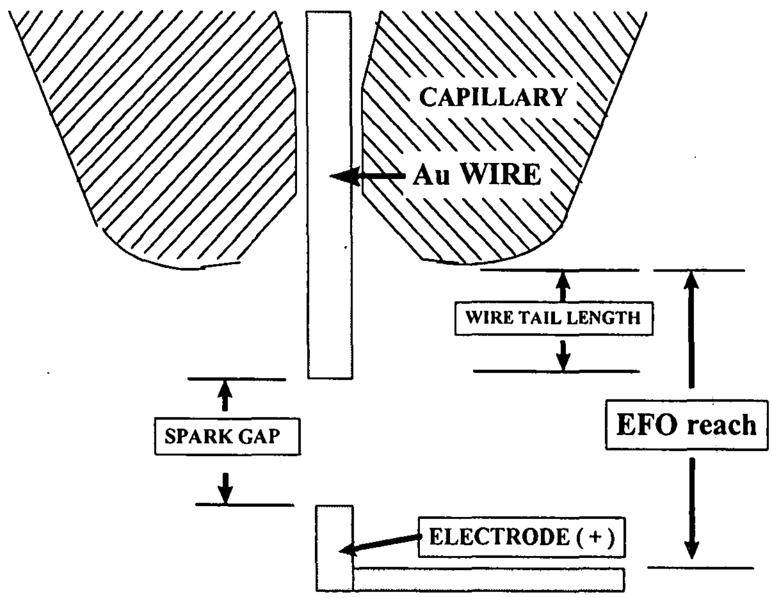
Figure 5. Capillary and Au wirebond Assembly and Parts. *The parts of the capillary: Face Angle(FA), Hole Diameter(H), Inside Chamfer(IC), Outside Chamfer(OC), Cone Diameter(CD), Chamfer Angle(CA), Capillary Face or Tip (F), and Weld Length(WL). The figure describes the location of the Ball Diameter(BD), Wire Diameter(WD), and Ball Height(BH) of the Au wire in the assembly.*

This paper will explore a way of circumventing adhesion problems by optimizing wirebond parameters by treating temperature as a noise factor and fixing metallization composition, etching and capillary geometry as constant factors. The novel feature of this procedure lies in the application of increased bonding temperature, a step which can confound results. The search for optimal setting is carried out using a combination of response surface analysis in conjunction with Taguchi analysis, two optimization methods that are usually applied separately. The optimized parameters are then used for some confirmatory runs.

The organization of the paper is as follows. Section 2 provides a short description of the wirebonding process. The description of the experimentation flow and the materials used are described in section 3. The statistical treatment is given in section 4. The highlights of the results are discussed in section 5. Finally, some concluding remarks and recommendations for future experimentation are given in section 6.

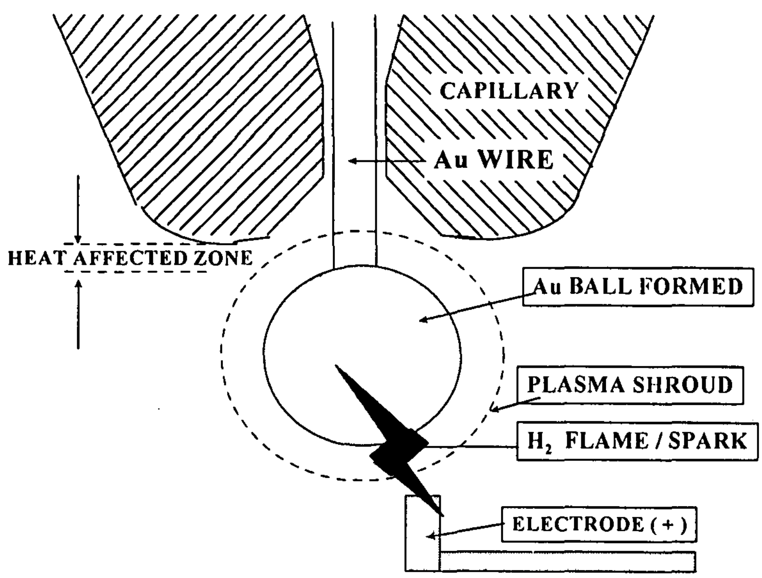
2. Wirebonding Process

Wirebonding process is the most significant of the IC assembly. It is where the electrical interconnections between the 'internal world' and the 'outer world' of the ICs are made. Interconnections are made through a metallurgical welding of approximately 99.995% Au

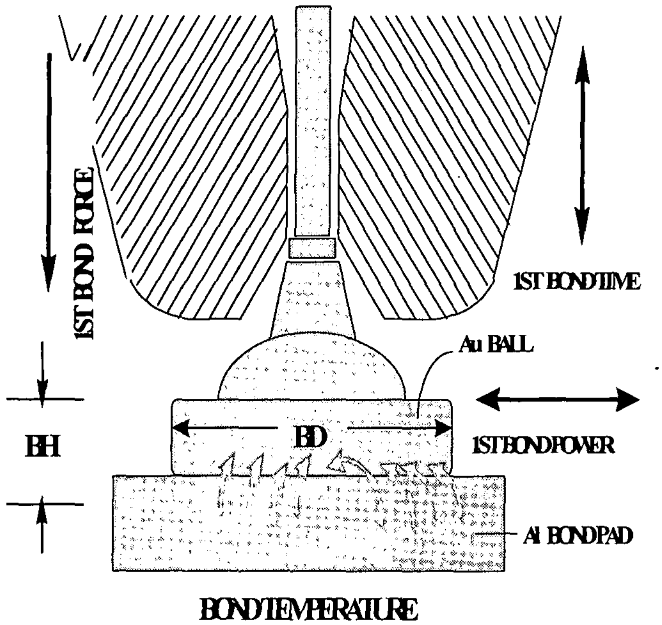


(a) EFO, Capillary, and Au wire assembly.

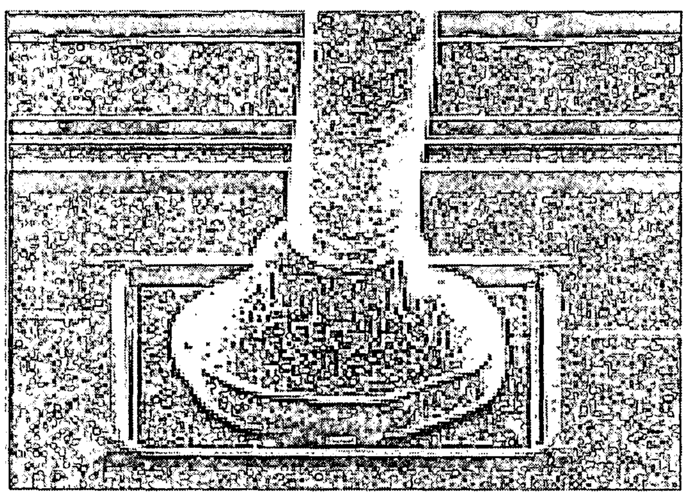
wire between the aluminized bonding pads and the inner lead fingers of a lead frame. Around 90% of the electrical connections to chips are carried out using wirebonding techniques.



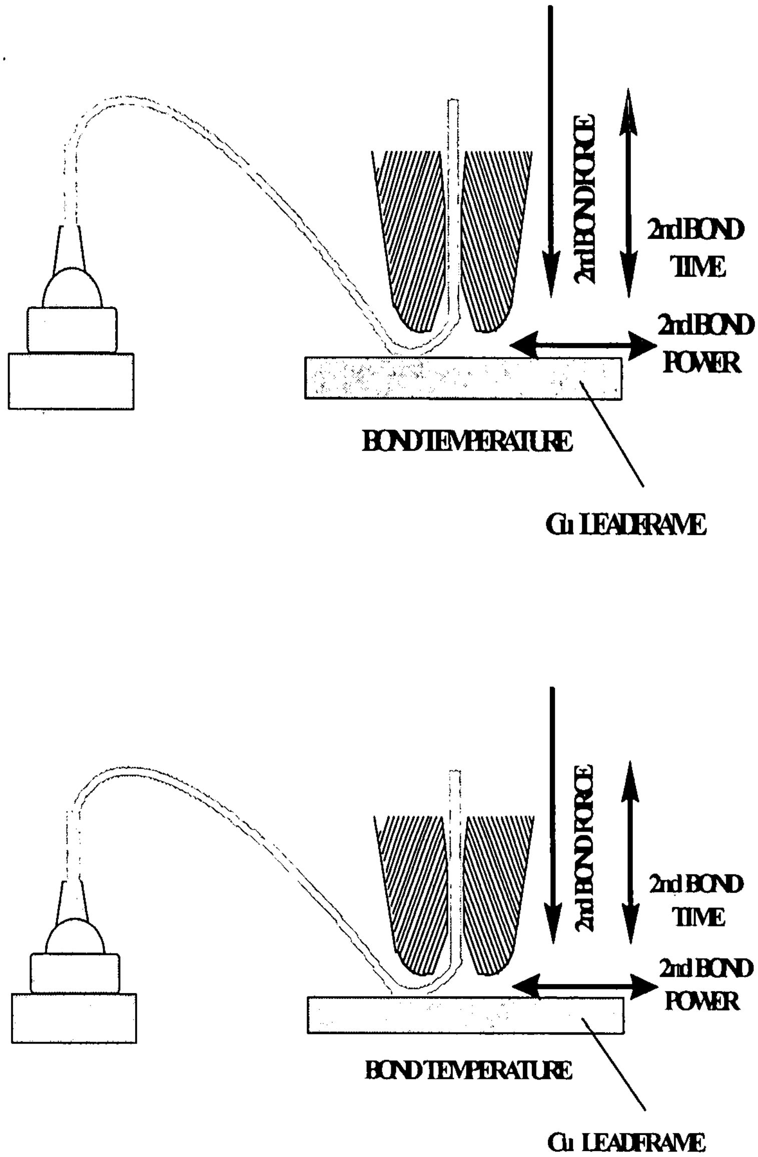
(b) Au Ball Bond Formation through EFO.



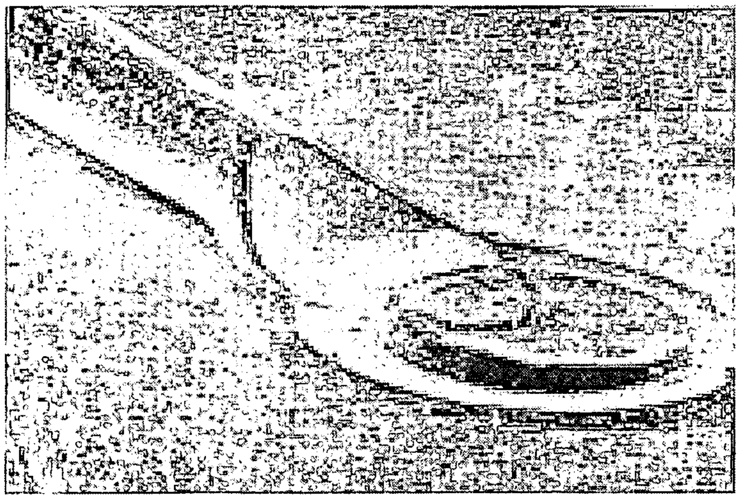
(c) Application of First Bond Parameters (Time, Power, Force) creating a metallurgical weld between Au and Al.



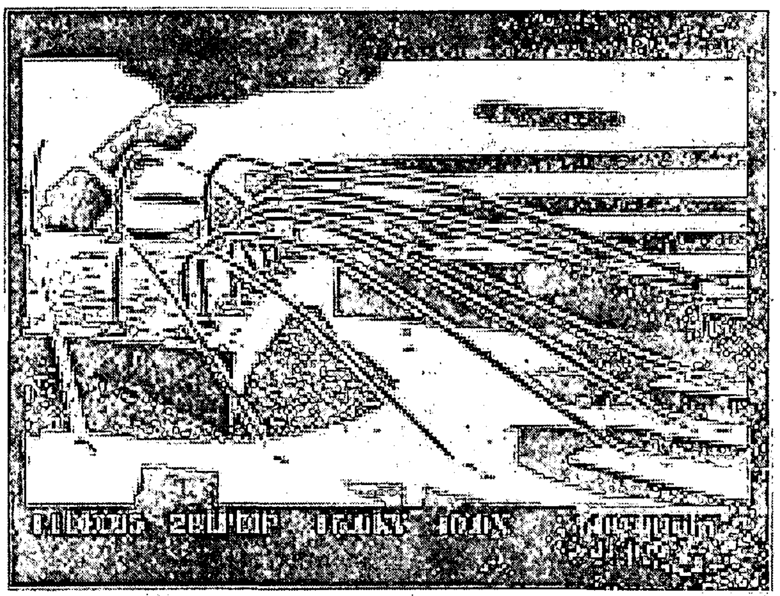
(d) SEM photo of Au ball bonded on Al bond pad.



(e) The Second Bond Parameters' application(Time, Power, Force).



(f) **SEM photo of the 2nd Bond.** *The stitch or the 2nd bond formation is dependent on the inner and outer chamfers, the capillary tip or face(F), the Face Angle(FA) with the application of the Bond Parameters.*



(g) SEM photo of the complete wirebonded unit.

Figure 6. The Complete Wirebond Process.

The most common bonding technique used in the industry is the so-called Thermosonic (TS) bonding process. It begins with ball formation done by melting the end of the Au wire. Before, a wire is melted through the use of a hydrogen (H) flame. Nowadays, a technique known as electronic flame-off (EFO) is used to melt the ball, whose size is around two or three times the wire diameter, depending on the spark conditions. The Au wire and the ball are surrounded by plasma (ionized air), completely encircling the ball by about 2 millimeters (mils) thick, extending up from the ball or the heat affected zone of the wire at about 4 mils (see Fig.6 a-g). Bonding is simultaneously accomplished through the application of a vertical load on the ball, while ultrasonically exciting the wire.

After the first bond (Au bond to Al bond pad) is created, the capillary then drags the Au wire to make a second bond. A wire loop and a wedge is bonded (stitched) under load and ultrasonic excitation. The stitch is dependent on the geometry of the capillary.
The TS method was developed to circumvent the problem induced by excessive temperatures on the metallography of the process - the rapid deterioration of Au and Al welding over time.

Punzalan (1996) argued that tool force, ultrasonic power, duration of the ultrasonic application (bond time) and heater block (bond temperature) are the major parameters to be considered in optimizing the bond process. Interdiffusion welding can also be enhanced by manipulating bond temperature. If we denote the penetration by X, the diffusion time by t and temperature by T, then we have the following relation due to Kohl (1989).

$$X = \sqrt{K(T)t}$$

and

$$K(T) = 5.2x10^{-4} \exp\{-Q / RT\}$$

where T is measured in °K; R is the gas constant (1.9885 cal/Kmol); and Q is the activation energy.

3. Experimentation

The physical features of the ball bond (height, diameter and outer weld area), ball shear test (BST) results, cratering test results, visual inspection test results, number of lifted ball bonds and percent intermetallic growth formation are of general interest. In particular, what happens to these variables when temperature is changed from 220°C to 240°C will be investigated. Amkor Anam Pilipinas, Inc. is currently using 220°C ± 20°C as its specification.

Several studies have been made already with the objective of eliminating ball bond adhesion problems. The principal challenge posed today is the possibility of redefining parameters settings under higher bonding temperature setting under which lifted ball bonds are intermittent. This is motivated by the theory that inter-atomic diffusion welding between Au and Al can be best developed through the application of increased bonding temperature.

The main parameters of interest include bond time, bond power and bond force. It is important not only to derive settings with high BST as it connotes good adhesion, but one that will show good ball bond features and proportional intermetallic growth formations. Temperature was not categorized as a main parameter since it is usually allowed to fluctuate during bonding operation in the line.

Inked dice of devices with bond pad metallization composition of Al-Si-Cu were bonded using 1.3 mils Au wire and a capillary with 8.0 mils Tip (F), and with CD of 2.9 mils. NaOH and KOH solutions were used to etch samples of each parameter run.

A standard baseline 1488 Turbo LQX wirebonder was used to bond the inked dice. A 1000X Hisomet microscope was used to verify the physical appearance of the ball after parameter application. A standard Dage Ball Shear Tester was used to determine the ball shear responses of the parameters used.

4. Optimization Procedure

Two competing procedures are usually employed in optimizing a response based on input parameters. Taguchi introduced a simple procedure utilizing signal to noise ratios as optimizing function with orthogonal arrays as core design for the experiment. Orthogonal arrays are attractive because they require fewer runs compared to classical designs such as factorial experiments and response surface designs. Taguchi's method has found numerous applications, see for example Kackar (1985), Lin and Kackar (1985), Phadke, et. al. (1982) and Taguchi and Phadke (1984).

Response surface methodology is an alternative procedure popularized by Box. Utilizing designs with properties such as rotatability and orthogonality, response functions are fitted to measurements using regression techniques. The fitted response surface is then examined for existence of curvature. Optimal settings are pinpointed by tracing the location of the curve's extrema using ridge analysis. If the search results in a ridge, a second experiment is implemented along the path of steepest ascent or descent and the analysis repeated. This continues until an optimum is established.

A baseline experiment was first conducted using a replicated 2^3 factorial design involving the bond parameters time (X_1), power (X_2) and force (X_3) with average BST readings (Y_1) as the main response of interest. A low Y_1 value is an indicator of adhesion problem. Separate factorial runs were performed at 220°C and 240°C. Each of the run was replicated 18 times (3 strips per run consisting of 6 units/strip). Aside from Y_1, average values of ball height (Y_2), ball diameter (Y_3), cratering test (Y_4), visual inspection test (Y_5), number of lifted ball bonds (Y_6) and percent intermetallic growth formation (Y_7) readings were recorded. Results of the experiment were used to determine a window settings of the parameters over which optimization will be conducted. The settings for the factorial run are given below.

Parameter	Low (-)	High (+)
X_1	10	40
X_2	50	90
X_3	50	90

Taguchi analysis was also used to optimize Y_1 (the larger the better) using temperature as the noise factor. The use of the technique can lead to a recommendation of a best setting within the experimental region, something that is not possible if the ridge analysis resulted in a stationary point.

Confirmatory runs were made to validate the desirability of the derived settings. Descriptive statistics were used to facilitate comparison of the derived setting with that used in the line.

5. Results

A prudent approach to optimization is the conduct of a baseline experiment - one which can provide a good window setting for the optimization stage. Usually designs which can only accommodate a linear response is used in order to limit the number of runs required. Table 1 summarizes the result of the baseline experiment, including the standard deviation of the BST readings obtained for each setting.

Table 1. Average BST (Y_1) results and the corresponding standard deviations for the 2^3 factorial experiment

Parameters			220°C		240°C	
X_1	X_2	X_3	Y_1	SD	Y_1	SD
-	-	-	43.01	5.04	41.44	5.61
+	-	-	66.58	5.37	70.57	6.06
-	+	-	76.07	4.14	76.18	4.36
+	+	-	80.42	6.97	87.33	6.16
-	-	+	60.85	6.79	52.06	5.90
+	-	+	77.00	6.39	79.43	5.17
-	+	+	85.45	6.27	84.63	6.12
+	+	+	90.41	4.53	93.84	4.88

The results in Table 1 show a general trend towards an increase in average BST as the temperature is increased from 220°C to 240°C, except at runs where time is set at the low level. Also, variability was more or less maintained. Note that higher average BST readings were recorded at the high setting of power for both temperature settings. It would then be logical to choose a window around the low level of time (40), high level of power (90) and high force (90). However, qualitative assessment of the ball bond features revealed that smashed balls occurred at - + + and + + +. Hence, the chosen window for the CCD run. Table 2 shows the result of the readings at both temperature settings.

Table 2. Average BST (Y_1) results and the corresponding standard deviations for the CCD runs

Parameters				220°C		240°C	
X_1	X_2	X_3	Run Type	Y_1	SD	Y_2	SD
0	0	+	Axial	68.19	10.39	71.29	9.30
-	+	+	Factorial	58.51	6.30	61.25	7.35
0	0	0	Center	59.63	4.94	74.72	9.28
0	0	0	Center	57.25	4.15	66.31	6.54
0	0	0	Center	52.60	5.33	65.47	6.07
0	0	0	Center	50.32	4.90	61.79	4.86
-	-	-	Factorial	28.47	3.53	37.91	5.07
+	+	+	Factorial	82.02	4.79	89.39	8.28
-	+	-	Factorial	42.36	4.62	47.01	4.21
+	-	+	Factorial	58.49	4.34	74.12	8.25
0	0	0	Center	56.14	2.87	70.17	7.58
0	0	0	Center	55.70	3.14	59.25	4.68
-	-	+	Factorial	43.62	6.65	46.17	6.59
0	0	0	Center	56.88	3.78	58.67	4.28
-	0	0	Axial	22.47	1.37	24.28	3.33
+	0	0	Axial	71.72	3.63	78.52	5.77
0	0	-	Axial	47.08	3.74	50.34	4.05
0	0	0	Center	64.04	5.03	63.04	4.64
+	-	-	Factorial	48.02	3.87	52.47	4.20
0	-	0	Axial	36.43	4.94	45.90	4.95
0	+	0	Axial	72.74	3.52	74.80	4.99
0	0	0	Center	56.29	4.00	59.08	5.06
+	+	-	Factorial	64.69	5.76	71.95	5.36

It is clear from the results in Table 2 that the increase in temperature resulted in the increase of average BST for almost all of the CCD runs. Hence it was decided that response surface analysis will be performed only for the 240°C results. The response equation takes the form

$$Y_1 = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (1)$$

where time, power and force were coded as follows:

Parameter	Low (-)	High (+)
Time	+1	+2
Power	+1	+2
Force	+1	+2

The ANOVA table for the CCD run at 240°C is given below.

Table 3. ANOVA results for the CCD runs

Source	df	Sum of Squares	Mean Square	F Value	p-Value
Time	2	2822.09	1411.04	46.88	0.0001
Power	2	871.38	435.69	14.47	0.0022
Force	2	706.40	353.20	11.73	0.0042
Time*Power	1	13.97	13.97	0.46	0.5150
Time*Force	1	34.40	34.40	1.14	0.3162
Power*Force	1	0.40	0.40	0.01	0.9110
Time*Power* Force	1	13.03	0.40	0.43	0.5290
Error	8	30.10	13.03		
Total	18		30.10		

The result shows that the interactions among the bond parameters are not significant. Contribution to total variability is dominated by bond time followed by bond power and then by bond force. Estimates of the coefficients in the response equation given in (1) are given below.

Table 4. Least squares estimates of the coefficients in equation 1

Parameter Coefficient	Estimate	p-Value
β_0	62.55	0.9707
β_1	14.98	0.0991
β_2	8.78	0.9645
β_3	8.25	0.8204
β_{11}	-7.28	0.1541
β_{22}	2.13	0.6651
β_{33}	1.66	0.7354
β_{12}	2.07	0.4782
β_{13}	1.32	0.6494
β_{23}	0.22	0.9384

The fitted response function has a R^2 equal to 82.34%, good enough for characterization purposes. However, the tests for the coefficients show insignificant results, indicating absence of curvature. Ridge analysis was also performed. The search resulted in the extraction of eigenvalues of mixed signs indicating a saddle stationary point. Hence the search for an optimal setting under 240°C failed. As far as the directional effect of the parameters, it can be seen that time has the greatest positive effect on BST, followed by power and then by force. Based on this, it is quite tempting to set the parameter window at the high levels of the bond parameters. It is for this reason that Taguchi analysis was used in the reanalysis of the data.

Since the objective is to maximize BST reading without degrading the integrity of the ball bonds, we take the option of minimizing $-\log_{10}\left(\frac{\overline{Y}_1^2}{s^2}\right)$. This is equivalent to selecting a setting with the least coefficient of variation (CV). The CVs for the CCD run is given in Table 5. The CV was obtained by pooling the results of each run irrespective of the temperature setting. The best setting would therefore be robust to temperature fluctuation..

Table 5. Coefficient of Variations produced by the CCD runs

X_1	X_2	X_3	Run Type	CV
0	0	+	Axial	14.29
-	+	+	Factorial	11.50
0	0	0	Center	10.81
0	0	0	Center	8.81
0	0	0	Center	9.70
0	0	0	Center	8.81
-	-	-	Factorial	13.21
+	+	+	Factorial	7.43
-	+	-	Factorial	9.90
+	-	+	Factorial	9.70
0	0	0	Center	9.03
0	0	0	Center	7.04
-	-	+	Factorial	14.71
0	0	0	Center	6.98
-	0	0	Axial	12.20
+	0	0	Axial	6.46
0	0	-	Axial	8.02
0	0	0	Center	7.61
+	-	-	Factorial	8.04
0	-	0	Axial	11.92
0	+	0	Axial	5.87
0	0	0	Center	7.99
+	+	-	Factorial	8.24

From the results given by Table 5, the setting with least CV is given by 0 + 0 followed by + 0 0 and then by 0 0 0. 0 + 0 corresponds to 20, 87 and 65 for time, power and force, respectively. At this setting, not only is BST high but variability is low as well. Qualitative assessment of the setting yielded good ball bond and intermetallic growth formations.

A separate set of runs was made using the following window setting.

Parameter	Low (-)	High (+)
X_1	15	20
X_2	70	87
X_3	60	65

At the bond window, the ball height is averaging at 0.9 mils; the ball area hovers around 9 mils; and the ball diameter ranges from 3.4 to 3.5 mils. The weld area is placed between 0.6 to 0.7 mils. Also in this window, BST is averaging from 60 to 70 g with expected maximum standard deviation of 5 g. The percent intermetallic growth formation is between 70% to 86%. As power and time increases, the ball height and the number of lifted ball bond decreases. On the other hand, as the parameters increase in level, the ball area, BST, ball diameter, weld area and percent intermetallic also increase.

The following are some observations regarding the effect of increased bond temperature at different parameter settings in the CCD:

1. At - 0 0, increased bond temperature has reduced almost 60% of the lifted ball bond defects. Furthermore, the ball diameter, ball area, and weld area were larger. The high temperature expanded the Au ball and reduction of lifted ball bonds was made possible by the increase in intermetallic growth. This was observed particularly at 0 0 0 and - - +.
2. Ball diameter was increased from 3.23 mils to 3.26 mils. The ball area was increased from 8.02 mils to 8.25 mils; while weld area improved to 2.09 mils from 1.86 mils. Lifted ball bonds were eliminated at runs 0 - 0, 0 0 0 and + - 0.
3. In general, BST response was increased at 240°C. Intermetallic growth formations has also increased, suggesting a positive correlation between the two response.

Confirmatory runs were done to benchmark the performance of the derived settings versus the settings used in the line. Comparison was made at both temperature settings. The table below summarizes the results.

Table 6. Comparison of the derived settings (optimized) versus line settings (unoptimized)

Setting	Ave. BST	SD
Unoptimized (220°C)	41.73	6.01
Optimized (220°C)	78.40	7.36
Unoptimized (240°C)	54.07	7.28
Optimized (240°C)	85.39	7.75

It can be seen from the Table 6e that the optimized parameters using 240°C has the highest average BST results. Note that the same temperature setting uniformly betters the BST readings. Also, note that the average is even higher than the expected reading of 74.80 g from the CCD experiment. Furthermore, the effect of the optimized parameters on the other physical features of the ball bond are as follows:

1. The obtained average ball height was 0.77 mils.
2. The average ball area was placed at 10.15 $mils^2$.
3. The outer weld area was 3.99 $mils^2$.
4. The ball diameter was measured at 3.65 mils.
5. Around 86% intermetallic growth formation was observed with no concentration from the center towards the ball sides (see Fig. 9).

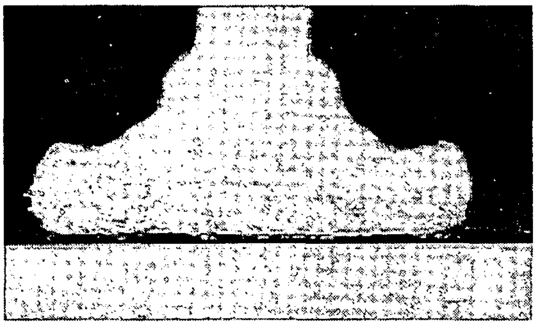


Figure 7. Metallography of unit bonded at optimized parameter with temperature at 240°C.

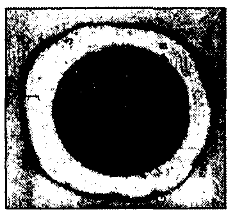


Figure 8. Ball bond characteristics of the obtained setting (Time = 20ms, Power = 87mW, and Force = 65g).

RUN21 240C
(0 + 0)

Figure 9. Intermetallic Formation of the obtained Optimized Parameter. *It can be seen that the growth is mostly concentrated at center of the ball and extending on the edges. Estimated %intermetallic is 80% to 86%.*

Figure 8 describes the appearance of the ball bond produced, while Fig. 9 shows the metallography of a unit bonded at 240°C. Finally, Fig. 10 shows the differencc between the parts per million (ppm) defect of the temperature settings benchmarked on a customer. The figure shows remarkable improvement in ppm trend reinforcing the effectiveness of the derived setting.

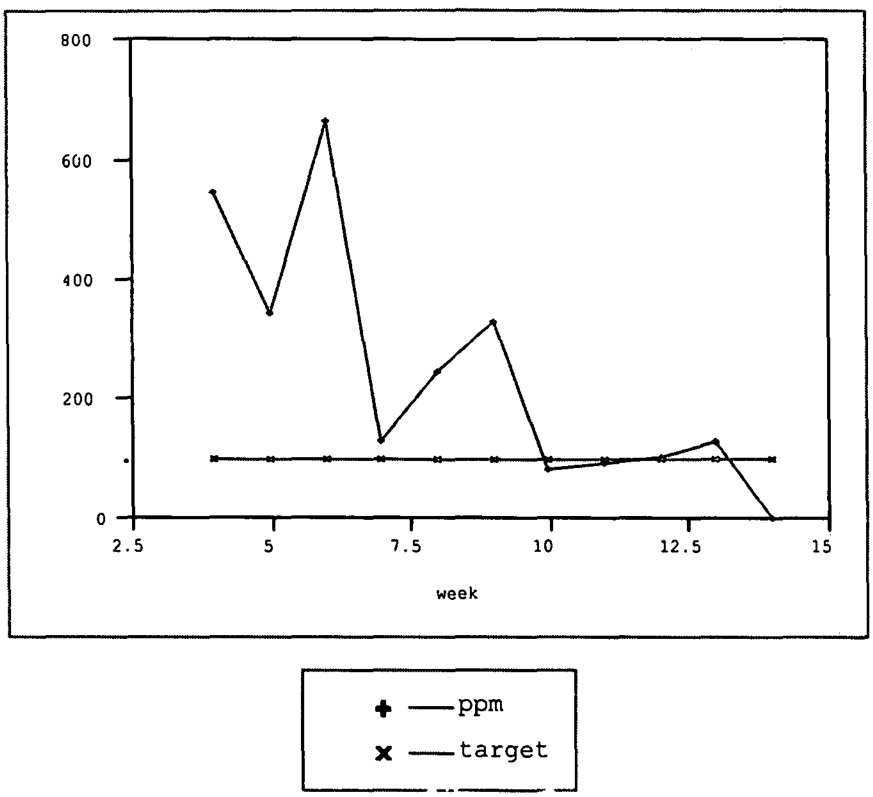


Fig. 10. Comparative ppm performance of the derived setting compared to the target ppm .

6. Concluding Remarks

In this paper, we show how a hybrid of two competing techniques can be used to eliminate adhesion problems in the wirebonding of ICs. Taguchi analysis was used to come up with an optmized bond parameter (time, power and force) setting using the coefficient of variation as the optimizing function and average ball shear test results, an indicator of good adhesion, as the main response of interest. Response surface analysis failed because the fitted function lacks curvature, a necessity for the derivation of an optimum setting. Temperature was not considered as a main factor since it is usually allowed to fluctuate in a window setting during wirebonding.

Comparison of the optimized setting (Time = 20ms, Power = 87mW, and Force = 65g) versus the setting used in the line showed that raising temperature to 240°C from 220°C increased ball shear test readings. Furthermore, good ball bond features characterized by better ball height, ball area, outer weld area, ball diameter and intermetallic growth rate. The derived setting was verified in a confirmatory run and implemented on a customer. Performance of the process showed improved levels of ppm defects.

The engineering application suggests that adhesion problems can be circumvented through the application of higher bond temperature. Therefore, it is very interesting to determine how a temperature range higher than 240°C will perform without damaging bonding reliability. In doing so, it is recommended that temperature be treated as a noise factor separate from the bond parameters. The effect of other factors such as metallization composition, capillary design and etching, when they are varied, is also of interest. Future applications should be done along these directions.

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