

Construction of Prediction Model for the Wire Bonding Process through the ANFIS

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Abstract

In the wire bonding process, different combinations of parameter values will directly affect wire bonding quality. The optimal combination of these parameter values is very important to ensure the overall process quality response. Therefore, it is necessary to investigate the effects and interactive relationship of the bonding parameters on the bonding quality. This paper chooses the response factors of shear strength and Squashed Ball Diameter (SBD) for the bonding quality evaluation. Through the design of experiments (DOE) method, 60 sets of experimental samples of the ball bond, varying 9 process parameters are manufactured and tested. The effect of the variation of these parameters on the shear force and SBD are analysed and 6 out of 9 parameters are determined to be controlling factors in the prediction model. Considering the difficulty in analysing the nonlinear and interactive relationships between the parameters and bonding quality, this paper proposes a process modelling approach based on an adaptive Neuro-Fuzzy Inference System. For the construction of the prediction model 50 sets of samples, where the 6 process control parameters are varied are prepared. These are used for the training of the process prediction model and a further 15 sets of samples are used for model validation. An error analysis is then performed to evaluate the model created. Based on the process prediction model, the characteristics of the bonding parameters affecting bonding quality are obtained, that can then be used for the optimisation of wire bonding process.

Key Words: Wire bonding, Process parameters, prediction model, Design of Experiment, Adaptive Neuro-Fuzzy Inference System (ANFIS)

1 Introduction

In the IC wire bonding process, there are many process parameters that have to be set properly to achieve a good bonding quality. It is evident that these wire bonding parameters are the main influencing factors not only on ball bond strength, but also on void formation [1]. Optimal combination of these parameter values will achieve a high bonding quality. Therefore, it is necessary to investigate the

bonding parameters and find out the effects and relationship of these process parameters on the bonding quality [2].

Optimising a wire bond process begins with a clear understanding of the machine set-up parameters, the response variables involved and their relationship to one another. Experimenting with these parameters is an important step towards developing a robust wire bond process. For this reason, a lot of effort has been

spent on optimising the bonding parameters and to reduce wire bond process variation [3, 4, 5]. Tan [3] presents an overview of thermosonic bonding and the machine set-up parameters to interpret the results of wire bond design of experiment (DOE) data. It concludes that ultrasonic power has the strongest influence on bond quality and visual appearance, because it controls the level of deformation of the bonding wire. Insufficient power can result in narrow, under-deformed bonds and tail lifts. Excessive power results in wire bonds with a 'squashed' appearance, heel cracks, cratering damage to the semiconductor die, undesirable build-up of residual bond pad material on the bonding tool and poor mechanical integrity of the wire bonds. Excessive bond deformation can occur if either the device being bonded is not properly secured or if the contact force applied to the bonding tool is too light. These can result in either mechanical chattering of the device or insufficient mechanical contact between the bonding wire, bonding tool and bond pad surfaces. Rooney [4] describes several different analytical techniques and the reliability testing used to evaluate the wire bonds. In the paper, an improved understanding of the wire bonding process was achieved by showing the dependence of the visual appearance of the wire bonds on wire bond process parameters. Liang [5] investigated the influence of wire bonding parameters on the bondability and ball bond reliability. By introducing the concept of a reduced bonding parameter, a combination of all bonding parameters, the authors are able to relate the bonding parameters to the bondability and ball bond reliability. Liu [6] has utilised the three-dimensional finite element method to simulate the wire looping process and studied the bonding loop parameter effect and residual stress distribution in the wire loop. Ding [7] studied the effects of bonding force on contact pressure across the bonded area and frictional energy in wire bonding. Shu [8] evaluated the important process criteria and bonding parameter interactions on loop profile characterisation using a statistical method—"response surface methodology (RSM)". Tay [9] and Srikanth [10] employed the finite element

code ABAQUS to simulate the wire bonding process and obtain a wire bond profile.

Therefore, the critical issue with increasingly finer pitch wire bonding required by industry at present are defining a prescribed combination of bonding parameters, so that each parameter can meet the packaging configuration constraints whilst maintaining the final bond quality. At present the packaging industry currently relies heavily on test data to determine the bonding parameters settings needed to meet the design requirements. This trial-and-error process is time consuming and cost ineffective [6]. Therefore, it is important to fully understand the effects of the bonding process parameters and their interactions to obtain the optimum parameter combination quickly. Considering the difficulty in determining and representing the nonlinear and interactive relationships between the bonding parameters and bonding quality, this paper proposes a process modelling approach using an Adaptive Neuro-Fuzzy Inference System (ANFIS). For the wire bonding modelling process, sets of experimental data are measured and used for the training the ANFIS prediction model. The error of the prediction model is then analysed with separate data and the effects and characteristics of varying the process control parameters on the bonding quality can be obtained and used to optimise the combination of bonding process parameter settings.

In this paper, Section 2 describes the experimental platform and analyses the DOE experimental data. In Section 3, the prediction models for the response factors of shear force and Squashed Ball Diameter (SBD) are created through the ANFIS and the effects and characteristics of the process parameters to the quality response are discussed. The conclusions made during this work are summarised in Section 4.

2 DOE of Bonding Process Parameters

2.1 Experimental Platform

The analysis of the wire bond process optimisation is initially conducted using a DOE approach. One objective of the DOE study is to vary the bonder

settings in a systematic way to maximise the test values of response variables, such as bond shear strength and pull strength. In this paper, due to the uncertainties of the bonding process, 9 parameters of the bonding process are investigated for the ball bond to determine which parameters influence the strength and quality of the bond. These process parameters are: ultrasonic power, binding force, time, temperature, contact velocity, ball size ratio, tail length, EFO (the Electronic Flame Off) gap and contact threshold. As

Kumar [11] observed, the most important measured responses of bonding quality are ball diameter, height of the deformed ball and shear strength. The shear strength and SBD are selected in this paper as the quality response factors of the DOE. After designing the experiment, the actual bonding trials are carried out on a K&S1488Plus machine. Table 1 shows the levels and ranges of the process parameters designed. Fig. 1 shows the DOE experimental platform and measurement tools used.

Table 1 Values and ranges of process parameters selected

Parameters	Ranges	levels	Unit
A-Temperature	200-240	200, 210, 220, 230, 240	°C
B-Contact velocity	40-110	40, 60, 80, 100, 110	mils/msecs
C-Time	8-20	8, 11, 14, 17, 20	msecs
D-Power	40-80	40, 50, 60, 70, 80	mwatts
E-Force	32-52	32, 37, 42, 47, 52	grams
F-Size ratio	2.0-2.8	2.0, 2.2, 2.4, 2.6, 2.8	no units
G-Tail length	100-160	100, 115, 130, 145, 160	tenth-mils
H-EFO gap	8-16	8, 10, 12, 14, 16	mils
I-Contact threshold	30-70	30, 40, 50, 60, 70	no units

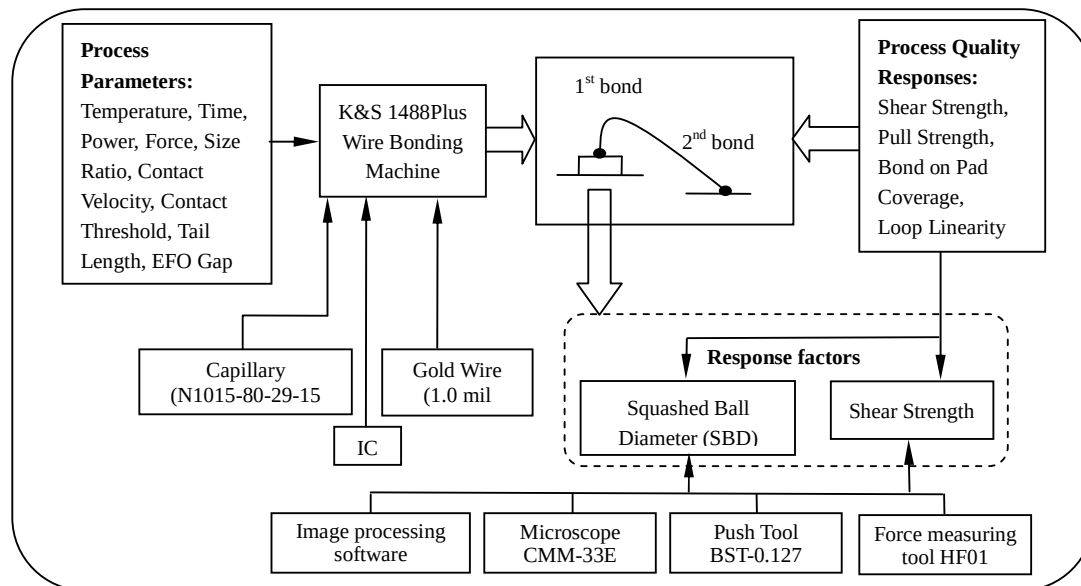


Fig. 1 DOE experimental platform and measurement tools used

Through these DOE trials, the combined effects of the 9 process parameters on the response variables can be measured and the process parameters that have the most influence on the bond quality can then be identified and used as the input parameters of process prediction model.

2.2 Analysis of Variance

The experimental data obtained from DOE trials is analysed by the method of ANOVA (Analysis of Variance) method. The ANOVA results for the shear force model and SBD model are shown in Tables 2 and 3. Through the comparison of the F-values for

the shear force model and SBD model in the two tables, we can determine that the ultrasonic power and then the temperature has the most effect on the bond shear force variable. The SBD is most influenced by the size ratio of the bond ball (EFO ball/wire) and the bonding temperature. From the analysis of the variance of DOE measurements and

the F-value comparison, 6 main process parameters are chosen for the further consideration. These 6 parameters and their ranges are detailed in Table 4 and the other parameters are set to a fixed value in the next series of tests. These values are: contact velocity = 60(mils/msecs), the tail length = 130(tenth-mils) and the contact threshold = 50.

Table 2 ANOVA analysis results for the shear force model

Source	Sum of Squares	dof	Mean Square	F-Value	p-value
A-TEMP	0.091	4	0.023	2.066	0.144
B-Velocity	0.018	4	0.004	0.408	0.799
C-TIME	0.027	4	0.007	0.621	0.656
D-POWER	0.141	4	0.035	3.201	0.049
E-FORCE	0.017	4	0.004	0.395	0.809
F-SIZE RATIO	0.04	4	0.01	0.916	0.484
G-TAIL LENGTH	0.013	4	0.003	0.305	0.87
H-EFO GAP	0.023	4	0.006	0.527	0.718
I-CONTACT THRESHLD	0.028	4	0.007	0.628	0.651
Residual	0.143	13	0.011		
Cor Total	0.553	49			

Table 3 ANOVA analysis results for the SBD model

Source	Sum of Squares	dof	Mean Square	F- Value	p-value
A-TEMP	363.314	4	90.8	2.108	0.138
B-Velocity	87.5606	4	21.9	0.508	0.7309
C-TIME	130.826	4	32.7	0.759	0.57
D-POWER	1038.73	4	260	6.027	0.0057
E-FORCE	101.059	4	25.3	0.586	0.6782
F-SIZE RATIO	1313.64	4	328	7.622	0.0022
G-TAIL LENGTH	34.0098	4	8.5	0.197	0.9354
H-EFO GAP	124.026	4	31	0.72	0.5936
I-CONTACT THRESHLD	87.6476	4	21.9	0.509	0.7306
Residual	560.139	13	43.1		
Cor Total	3523.97	49			

Table 4 Main process control parameters for the prediction model

Parameters	Ranges	Unit
A-temperature	200-240	°C
B-Time	8-16	msecs
C-Power	40-80	mwatts
D-Force	32-52	grams
E-Size ratio	2.0-2.6	no unit
F-EFO Gap	8-16	mils

3 Process Prediction Model and Effect Analysis

3.1 Prediction Model Establishment

The process model for the wire bonding can be described as follows:

$$[y_1(t), y_2(t)] = f(x_1(t), x_2(t), \dots, x_n(t)) \quad (1)$$

Here, $x_1(t), x_2(t), \dots, x_n(t)$ represents process parameters, such as the control factors of ultrasonic power, bonding temperature, bonding time and contact force, etc. $y_1(t)$ and $y_2(t)$ are the

response variables of shear force and SBD, respectively, where $f(\cdot)$ is a multi-variable nonlinear function.

The structure of the prediction model of wire bond process is illustrated in the Fig. 2. Based on the input of the process parameters, the model produces a prediction y'' , the difference between y'' and the

measured value y' will be fed back to and correct the prediction model, this procedure continues until the error is sufficiently small. Through the model created, the corresponding relationship between the process parameters and their response variables can be studied, and the optimisation of parameter combination can be achieved.

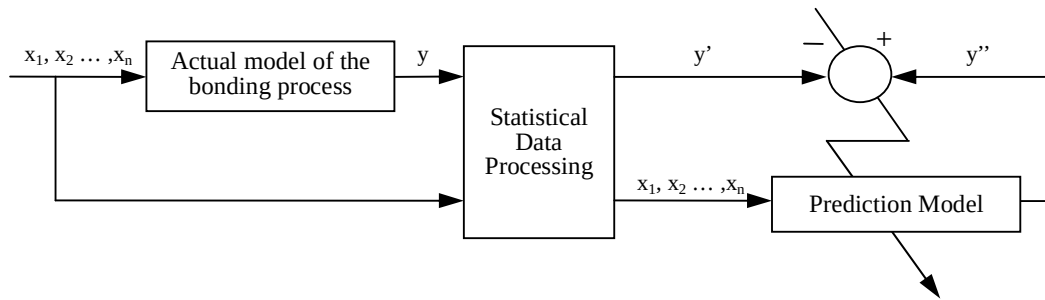


Fig. 2 Structure of prediction model of wire bonding process

There are many methods to establish a prediction model, such as the traditional methods of time sequence and regression equations, whilst the modern intelligent methods use neuro networks, fuzzy reasoning systems and genetic algorithms. Combining the fuzzy reasoning system with a neuro network, the adaptive Neuro-Fuzzy Inference System (ANFIS) has been widely applied in the prediction domain. The ANFIS adjusts the control parameters and response factors through the algorithm of back-propagation and least square methods.

The process prediction model in this paper is constructed by using the ANFIS method. For the construction and training of the model, 50 sets of trial samples are designated as training data. According to the ANFIS system, the numbers of input subjection functions for the shear force model and SBD model are set to [3 2 3 2 2 2] and [2 2 2 2 2 2], respectively. The input subjection functions are all set to be a Gauss function and the output subjection functions are set to be a constant value. Based on the basic settings, the ANFIS-based prediction model is implemented through the ANFIS Editor GUI module of the Matlab software. In the software, the hybrid-study algorithm is selected as the training method of the ANFIS. As a result, the shear force

model is created and has an error of 2.5028N after 25 iterative epochs, and the SBD model is also created and reaches an error of 0.35 μ m after 100 iterative epochs. The shear force model produces 144 (= 3 $\times$ 2 $\times$ 3 $\times$ 2 $\times$ 2 $\times$ 2) rules, the SBD model produces 64 (= 2 $\times$ 2 $\times$ 2 $\times$ 2 $\times$ 2 $\times$ 2) rules. These rules cover the whole range of the parameters selected in Table 4.

In order to verify and evaluate the prediction model created, 15 separate sets of test data from the trials are entered into the predicted model and the output values of the response factors of shear force and SBD from the prediction model are compared with the actual shear force and SBD measured. The prediction error can therefore be obtained. Fig. 3 shows the comparison of the predicted shear force with the measured one from which the error can be calculated. Fig. 4 displays the comparison of the predicted SBD with the measured SBD. From the error analysis, it is found that the mean error and variance for the predicted shear force are 3.16% and 0.012 and for the predicted SBD are 1.24% and 1.37, respectively. Table 5 lists the error analysis results which are based on the error produced over 15 sets of test data. From these results, it is concluded that the prediction models created reflect a true representation of the bonding process. The prediction model could

be further improved by increasing sample sizes

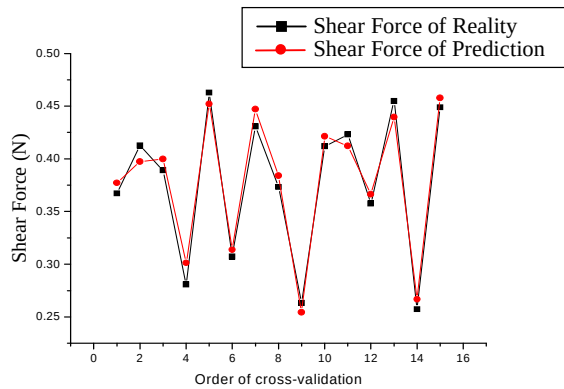


Fig.3 Error comparison of the shear force

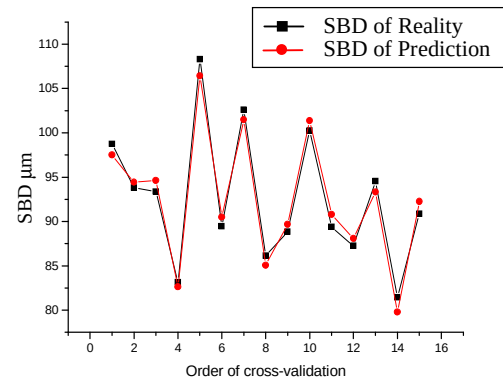


Fig.4 Error comparison of the SBD

Table 5 Error analysis for the 15 sets of trial data

Error Analysis	Mean Error (%)	Variance	Max Error (%)
Response factors			
Shear force	3.16	0.012	7.34
SBD	1.24	1.37	2.06

3.2 Effect Analysis of Process Parameters

Based on the predicted process model, the effects of these control parameters on bonding performance can be determined. Fig. 5 presents the relationship of bonding temperature and power to the model response variables of shear force and SBD. This surface model is obtained under the parameter settings of bond time = 10ms, contact force = 45grams, ball size ratio = 2.4 and EFO gap = 14mils. In this figure, shear force is at a minimum when the temperature and power values are low, but increasing the temperature and power values to 220°C and 80mw respectively, the shear force increases quickly to a maximum. The SBD variable has the similar relationship as the shear force, except that the power has more of an influence on the SBD than the temperature does, as shown in Fig. 5b). Therefore a considerable reduction in the SBD for minimal loss of bond shear strength can be achieved by reducing the power setting during the bonding process.

To better understand the effects and relationships of these parameters, the curves showing the variation of shear force and SBD with different with the power settings when the temperature is set to

200°C, 220°C and 240°C shown in Figs. 9 and 10. Examining Fig. 6 it can be seen that after the shear force reaches its maximum value at 65mw, it remains virtually constant thereafter. This situation happens in reality, as increasing bonding power will cause a larger vibration amplitude in the capillary which will damage bond interface and increase the chance of contamination, so reducing the bond strength. Then in Fig. 7 it can be seen that the ultrasonic power has a significant effect on the SBD as the power increases from 40mw to 80mw the SBD increases by approximately 13.5μm in each case.

Using a similar method of analysis, the relationship between bonding force and power can also be obtained from the prediction model. The change of ultrasonic power will affect the values of shear force and SBD. As shown in Fig.8, the shear force increases linearly as the bonding force increases. However the SBD is relatively insensitive to changes in the bonding force and remains almost constant, shown in Fig. 9. Therefore, the bonding force does contribute to the bonding strength and quality, sufficient force must be used to ensure a suitable bond quality, but an excessive force will cause the die to break and possibly damage the bonding pad. With

this example, the SBD cannot be reduced by reducing the bonding force, so the correct parameters to

choose would be the lowest bonding force and power settings to achieve a suitable bond strength.

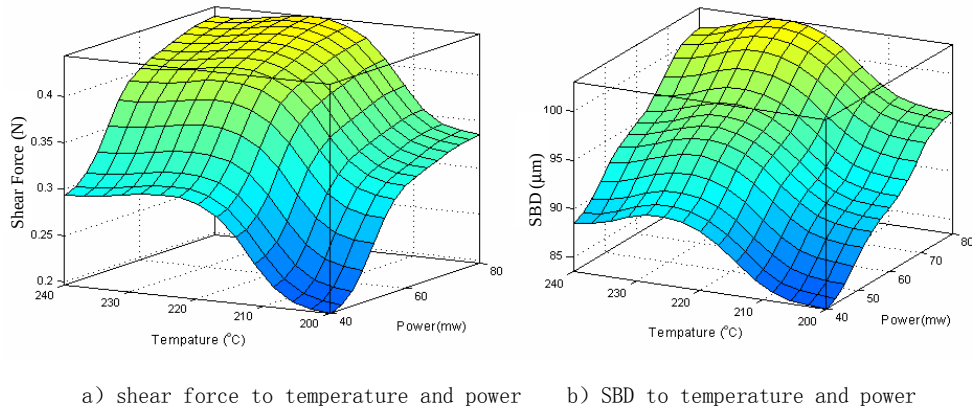


Fig. 5 Relationship of the bonding temperature and power to the response factors of shear force and SBD in the process prediction model

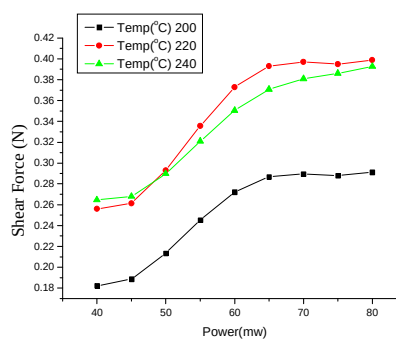


Fig.6 Shear force changing with the power under different temperature

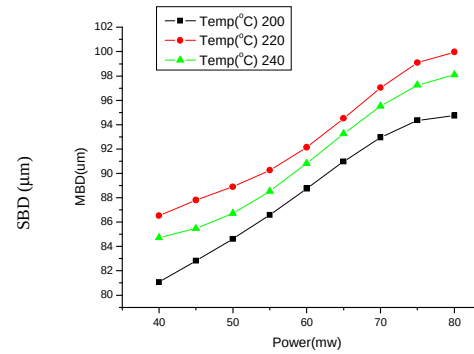


Fig.7 SBD changing with the power under different temperature

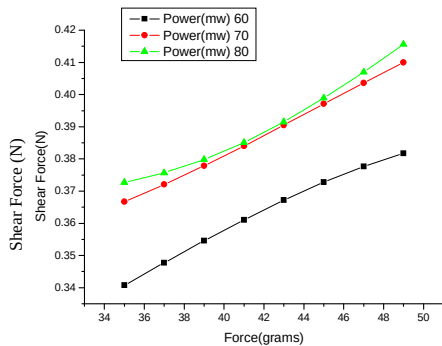


Fig.8 The relationship of bonding force and shear force under different power values.

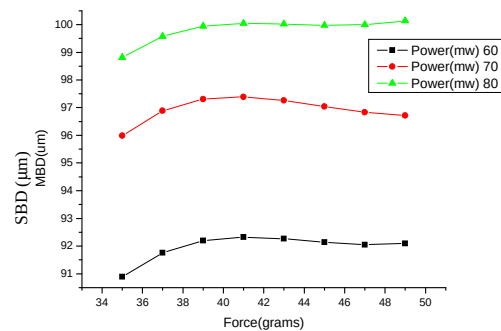


Fig.9 The relationship of bonding force and shear force under different power values

4 Conclusions

Based on the analysis of variance of DOEs, 6 process parameters are identified in this paper as control parameters for bonding quality control. The 6 parameters are bonding temperature, time, ultrasonic

power, bonding force, ball size ratio and EFO gap. The shear force and SBD are chosen as response factors to determine bond quality. Through the ANFIS system, this paper constructed a prediction model for wire bonding process, which can be used to

solve the difficulty of a mathematical representation of the bonding quality and process control parameters due to their nonlinear and interactive relationship. From the error analysis of the response variables for shear force and SBD from the prediction model created, it is found that the mean error and variance for the shear force and the SBD are 3.16% and 0.012, and 1.24% and 1.37, respectively. Based on the prediction model, the effects and relationships

between the control parameters and the response factors are obtained, which can then be used to produce an optimal combination of process parameters for the wire bonding process. Further work is to be carried out on the development of a software tool to enable the optimisation of the wire bonding parameter combinations based on the work conducted in this paper.

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