Preprint. Submitted for publication in the proceedings of
ICSJ 2018 – 8th IEEE CPMT Symposium Japan, Kyoto, Japan, November 19-21, 2018

Experimental investigations on the impact of bond process parameters in two-dimensional ultrasonic copper bonding

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***Abstract*—Ultrasonic bonding and welding are common friction based approaches in the assembly of power electronics. Interconnections with cross-sections of 0.3 mm² up to 12 mm² made from copper are well suited in high power applications. For increasing friction energy, which is responsible for bond formation, a two-dimensional vibration approach is applied to newly developed interconnection pins. Using two-dimensional vibration for bonding requires identification of suitable bonding parameters. Even though simulation models of wire bonding processes exist, parameters for the two-dimensional pin-bonding process cannot be derived accurately yet. Within this contribution, a methodology and workflow for experimental studies identifying a suitable bond parameter space are presented. The results of a pre-study are used to set up an extensive statistical parameter study, which gives insights about the bond strength change due to bond process parameter variation. By evaluation of electrical data captured during bonding, errors biasing the resulting shear forces are identified. All data obtained during the experimental study is used to build a statistical regression model suitable for predicting shear forces. The accuracy of the regression model's predictions is determined and the applicability to predict process parameters or validate simulation models is assessed. Finally, the influence of the tool trajectory on the bond formation is determined, comparing one dimensional, elliptic and circular trajectories.**

Keywords—ultrasonic two-dimensional bonding, electrical interconnection, process parameters

I. INTRODUCTION

Wire bonding is a commonly used process in the electronic package industry. Since it is a prevalent process, improvement of the bonding process is a promising goal to ensure high quality and long lifetime of electronic assemblies and thus saves costs and resources. A common goal of ongoing research is to improve the bond quality determined by the bonded area and the measured shear force. A number of sub-aspects of the bonding process, influencing the bond formation, have been studied in the past. One of the key aspects is a model for weld formation based on the friction energy induced in the contact zone between the work piece and the substrate [1] [2]. The influence of wear [3] and geometry of the tool [4] on the normal pressure distribution and the influence of the geometry of the tool on the transmittable tangential force [5] of different bond processes have been studied and modelled. In [6] a rarely considered aspect, the substrate resonance behaviour, was studied. All prior mentioned studies deal with copper-wire and copper-pin bonding, but lack information about the variance of shear forces. A study to predict the resulting shear force and its variation on basis of measured electrical process data has been presented in [7]. The presented neural network model is based on thousands of bonds of only one input parameter setup and cannot predict shear forces for different parameter setups. Even though many aspects of two-dimensional pin bonding are well understood already, the prediction of optimum process parameters for defined shear forces by use of simulation models is not possible yet.

Within this contribution, an experimental workflow for deriving a regression-based model predicting shear forces in dependency of process input parameters is presented. It will be shown how to sort out bonds, which have been built at non-stable process conditions, based on electrical data obtained during bonding. The influence of different tool trajectories on the shear force is analysed as well.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. It consists of a transducer generating two-dimensional vibration, a substrate holder and a lever mechanism for applying weights providing the normal force for the work piece. The pin used as a work piece is depicted in Fig. 2. Electrical data measured during the bonding process are time signals of the voltages and currents of the ultrasonic transducer.

III. IDENTIFICATION OF PARAMETER SPACE

Former research [8] showed that statistical models can be used to evaluate the influence of different bond process parameters on the shear force. A statistical regression model was used to derive the influence of each parameter on the bond result. The ultrasonic voltage, which is typically split in two phases, was simplified to only one voltage level within the underlying study, Fig. 3.

DOI: 10.1109/ICSJ.2018.8602653

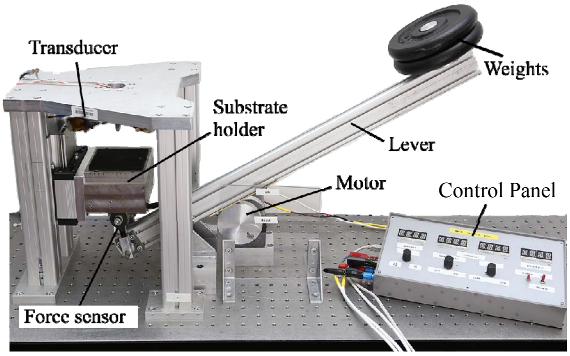

Fig. 1. Experimental setup for two-dimensional bonding

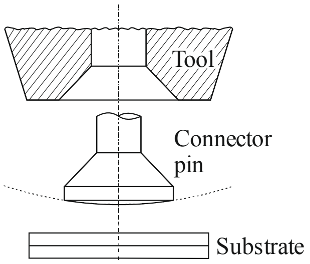

Fig. 2. Tool, pin, substrate assembly used for experimental setup

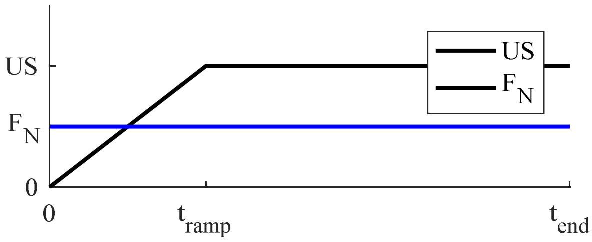

Fig. 3. Amplitude of sinusoidal ultrasonic voltage US and normal force F_N used for bonding

Following the experimental methodology of [8], ultrasonic voltage, bond normal force and bond duration are varied. The voltage ramp time t_{ramp} is kept constant. In contrast to [8], the parameter space of the statistical study is determined with the use of a minor pre-study instead of deriving parameters from wire-bonding processes. The pre-study relies on a "full-factorial" parameter combination experiment. The parameter limits for the pre-study result from test rig limitations, process limitations and economic limits. The economic limit is the maximal bond duration, which should not be exceeded so that the bonding process can still compete with soldering. Increments of each parameter are defined such that the total number of bonds needed for the study is held low, but provides a resolution which is high enough to set the subsequent parameter study up accurately. Therefore, each parameter set is bonded once. Doing so, the pre-study does not provide information about repeatability, but the parameter space which provides good shear forces should show a high density of bonds with high shear forces. Regions of poor bond process parameters should be indicated by shear force values of 0 N or by low shear forces. The results of the shear force measurements of the pre-study in dependency of the bond process parameters is depicted in Fig. 4. Based on the results of Fig. 4, parameter limits for the subsequent D-optimal parameter study are set to 41.7 % and 83.3 % for the ultrasonic voltage, to 42.9 % and 100 % for the normal force and to 18.8 % and 56.3 % for the duration respectively. Values are rounded to discrete step sizes of the non-normalized quantities. The limits should ensure to cover the edges of the parameter space, where shear forces reached are still acceptable. But not every parameter combination within those limits will lead to good bond results. In the pre-study the pins sometimes penetrated the substrate deeply, which is unwanted. Large penetration depths happened when high ultrasonic voltages and low normal forces were used at the same time. Thus, the upper limit of the normal force is extrapolated from 71.4 % within the pre-study to 100 % within the D-optimal parameter study. The duration was limited since short durations already provide good shear forces. To be compatible with the soldering process, time limit was decreased, while normal force was increased.

With parameter limits set up properly, the extensive statistical parameter study is designed using a "D-optimal" experimental design approach. Cornerstone® software designs a list of 15 different parameter combinations with use of the limits stated above. For gaining information on repeatability and standard deviation of the resulting shear forces, each parameter combination was bonded 15 times.

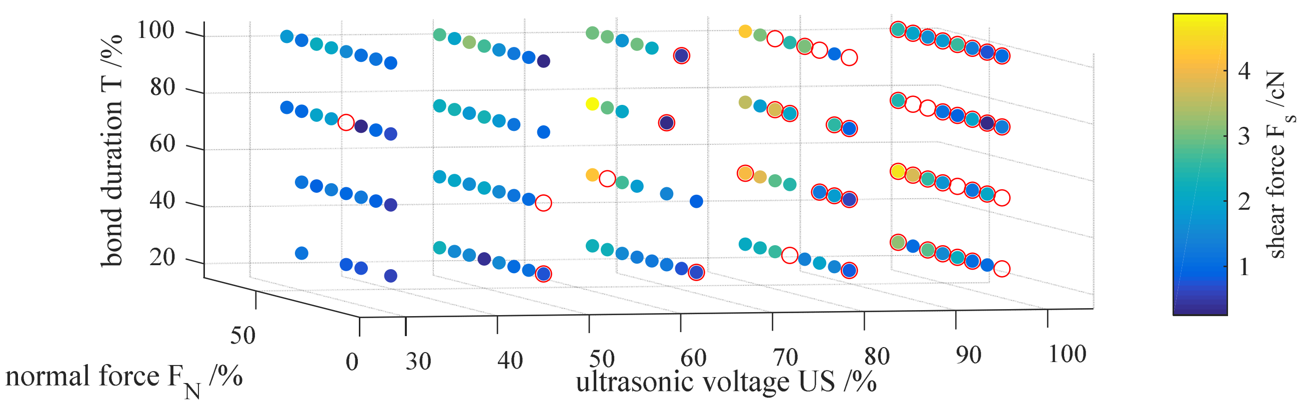

Fig. 4. Shear forces of pre-study in dependency of bond process parameters. Red circles indicating bonds with errors identified from electrical data. Missing dots indicate that pins did bond to the substrate.

For each parameter combination, ultrasonic voltage and normal force are applied according to Fig. 3. The second transducer voltage is controlled so that the currents of first and second transducer axes match each other in amplitude and are always 90 ° in phase to each other (circular trajectory).

After bonding, electrical measurements of the amplitudes of the ultrasonic voltage, the resulting electrical current amplitudes and the operation frequency of the ultrasonic transducers were evaluated. Three errors occurred repetitively during the bonding process and had to be considered before the statistical model was build, see. Fig. 5. First error occurring is a shifting of the ultrasonic frequency to the next higher harmonic. During about 2.3 % of the bond tests, ultrasonic frequency was shifted due to yet unknown effects, but mostly at ratios of high ultrasonic voltages and low normal forces. Second, at about 18.7 % of the bonds, the current at one or both of the transducer channels exceeded its limit and the channel was shut off. Third, at about 22.2 % of the bonds the voltage limit of the slave channel was reached without gaining same currents at both channels. Since the three effects also occurred in combination, the total share of bonds to be sorted out was 28.4 %.

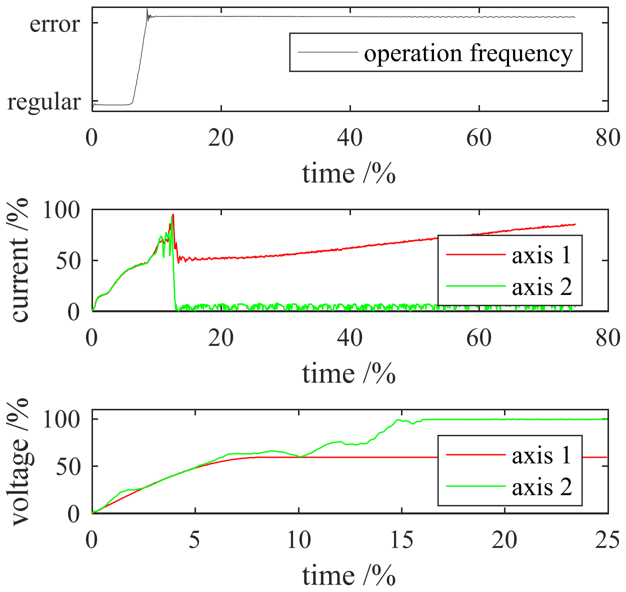

Fig. 5. Errors identified by analysis of electrical data. Top: Shifting operating frequency to higher harmonic; mid: shut down due to current protection; bottom: reaching of the amplifier voltage limit, leading to a non-circular trajectory.

IV. REGRESSION MODEL

The regression model was built using the software “Cornerstone®”. The regression model is a mathematical model and is a combination of a sum of terms given in equation (1). Each term included in the regression model was selected from a list, thus the model fits the measurement data at its best. The model consists of at least one parameter (x_n, $n = i, j, k, l$), called “predictor”, and is multiplied with a pre-factor (α_i, β_j, γ_k). The final regression model is built of the sum of terms and predicts the output value, called “response”, based on the predictor values. TABLE I. summarises the predictors and pre-factors selected within the underlying regression model, Fig. 6 shows the regression model.

The regression model is evaluated by comparing shear force predictions of the regression model with shear force measurements of newly and repeatedly bonded interconnections. For assessing the accuracy of the model, the mean values of measured shear forces are used. A summary of the parameters used for bonding, the predicted shear forces and the resulting deviation of the simulated and measured shear forces are summarised in TABLE II.

$$shear\ force = \sum\alpha_i \times x_i + \sum b_j \times x_j^2 + \sum\gamma_k \times x_k \times x_l \quad (1)$$
$$k \neq l$$

TABLE I. SUMMARY TABLE OF PREDICTORS AND PRE-FACTORS USED WITHIN REGRESSION MODEL

Predictor name	Coefficient	Units
Constant	0.64676	cN
Duration	0.04309	cN / %
Force	0.02906	cN / %
Voltage	0.00016	cN / %
Duration * Voltage	0.02618	cN / %²
Duration²	0.04312	cN / %²
Voltage²	0.51 e-8	cN / %²
Force²	0.02070	cN / %²

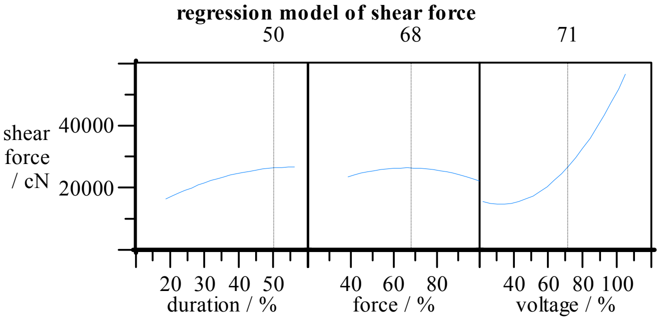

Fig. 6. Regression model results of shear force in dependency of process parameters, shear force of selected parameters is 24427 cN

TABLE II. SUMMARY OF MODEL ACCURACY

Duration / %	Voltage / %	Force / %	Pred. shear force / cN	Dev. of shear force / %
25	55	66	13137	-18.3
25	80	84	23614	0.8
50	68	71	24427	-21.0
50	80	84	31302	-14.5
37.5	46	86	13364	10.16

As can be seen in the results summary in TABLE II. , the predicted shear forces are mostly underestimations of the measured mean values. The maximal underestimation is -20 % from the measured mean value. The total accuracy of the model, expressed as a value of the adjusted residual squared, is 0.77. Compared to the accuracy of the model presented in [8], adjusted residuals squared could be improved by 0.23 due to elimination of faulty bonds. Results imply that the application of statistical models are acceptable for setting up processes with a bigger safety margin over a broad parameter range.

V. ANALYSIS OF THE INFLUENCE OF THE TOOL-TRAJECTORY

For investigating the impact of the two-dimensional, elliptical vibration trajectory on the bond strength, the shear force values were evaluated for different ratios of the ellipse-half-axes of the tool-tip trajectory, see Fig. 7. The shear force values rise with increasing ratio of the half axes, indicating that the frictional work in the contact between work piece and substrate is increased. The maximum shear force value is reached by a circular trajectory. The shear force value from a pure linear to a full circular trajectory can be increased by a factor of 3.22, which is even more than the theoretical value of 1.57 calculated in [9]. The reason for this increase might be the elasticities of the real bond connection, which have been neglected in the theoretical calculation of [9]. Due to the elasticities, there can be significant sticking-phases in the one-dimensional trajectory, while in the circular trajectory only sliding occurs. Hence, the amplification of frictional work is increased even more than expected. The rising scattering with increase of the ratio of the half axes seems to be caused by an increasing amount of current fluctuations, which are caused by the control of the second axis current regulation. These fluctuations seem to be caused by changing contact states when the pin tends to rotate, which was already identified within [8].

VI. CONCLUSION

Within this contribution, a step-by-step methodology to identify parameter spaces experimentally, to build a regression model for shear force prediction has been presented. Steps performed started from setting up rational limits based on process or test rig limitations. Next step was the full-factorial parameter study and analysis of the captured electrical data during bonding. Subsequently newly identified limits were used and a D-optimal parameter study was designed. After selection of only valid bonding results, the regression model was built with the residing shear forces and their process parameters. The three errors adversely affecting statistical results have been identified. In the end, a regression model predicting shear forces from process parameters was assessed. This statistic model can be used to predict shear forces and estimate the bond process parameter interrelation for a broad parameter space. Finally, the influence of the trajectory of the tool on the bond result could be shown.

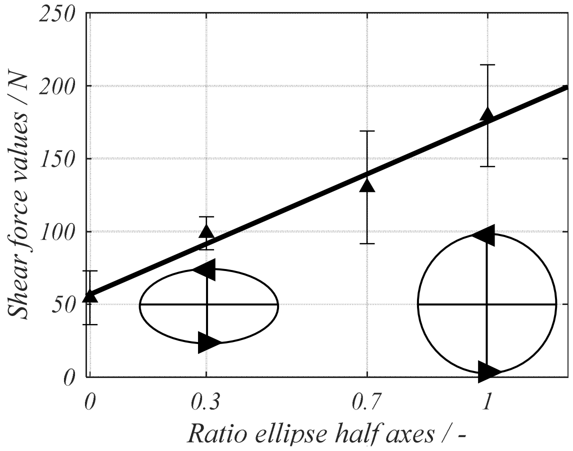

Fig. 7. Shear force values of bonded connector pins for different half axes relations of the tool-tip trajectory.

VII. ACKNOWLEDGMENT

This research was supported by ERDF.NRW (European Regional Development Fund in North Rhine-Westphalia) and Infineon Technologies AG.

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