Numerical and statistical investigation of weld formation in a novel two-dimensional copper-copper bonding process

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***Abstract*—State-of-the-art industrial compact high power electronic packages require copper-copper interconnections with larger cross sections made by ultrasonic bonding. In comparison to aluminium-copper, copper-copper interconnections require increased normal forces and ultrasonic power, which might lead to substrate damage due to increased mechanical stresses. One option to raise friction energy without increasing vibration amplitude between wire and substrate or bonding force is the use of two-dimensional vibration. The first part of this contribution reports on the development of a novel bonding system that executes two-dimensional vibrations of a tool-tip to bond a nail-like pin onto a copper substrate. Since intermetallic bonds only form properly when surfaces are clean, oxide free and activated, the geometries of tool-tip and pin were optimised using finite element analysis. To maximize the area of the bonded annulus the distribution of normal pressure was optimized by varying the convexity of the bottom side of the pin. Second, a statistical model obtained from an experimental parameter study shows the influence of different bonding parameters on the bond result. To find bonding parameters with the minimum number of tests, the experiments have been planned using a D-optimal experimental design approach.**

Keywords—ultrasonic wire-bonding, bond-tool design, parameter identification, statistical engineering

I. Introduction

Compact high power electronic switching modules increasingly demand bonded copper-copper interconnections with increased cross sections, [1], [2]. Using copper-copper instead of aluminium-copper as interconnection materials increases junction temperature and lifetime [2], [3]. On the downside, the process parameter window of standard bond machines is decreased and shifted to higher force and ultrasonic voltage [3], [4] because more frictional energy is needed to build the interconnection [5]. Since an increase of normal force and vibrational amplitude (steered by ultrasonic voltage), might damage the substrate or interconnection zone itself, [1], [2], [6] setting up robust processes gets difficult. Multi-dimensional vibrations, like planar circular rotation, allow to increase friction energy by lengthening the friction path without the drawback of increased stress [6], [7], [8].

To achieve at least two-dimensional, circular vibrations the bonding machine must be equipped with a new ultrasonic transducer and its electronics. Additionally, the bonding tool must be adopted for the transfer of energy to the interconnection zone, considering appropriate pressure distribution as well as guidance of the bonding work piece. Finally, bonding parameters have to be found. These aspects will be addressed within the next chapters.

II. Development of a Novel Bonding System for Nail- Like Pins

Based on an existing transducer for two-dimensional flip-chip bonding [6] a new laboratory system for bonding nail-like pins on substrates was set up, see Fig. 1. In contrast to conventional ultrasonic bonding systems, the transducer is fixed while the substrate holder can move vertically. A constant bonding force is applied via a lever mechanism and variable weights. The substrate-holder is actuated by an electrical motor. Before touchdown, the velocity of the substrate holder is reduced to prevent damage to the substrate. During the bonding process, bonding force is measured using a force sensor.

Fig. 2 shows the transducer, which in detail consists of four combined ultrasonic transducers, together with the specialized tool [4], the connector pin to be bonded and the arbitrary substrate. The system is driven by two phase-shifted voltages to

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generate the desired two-dimensional vibration of the tool-tip at 20 kHz.

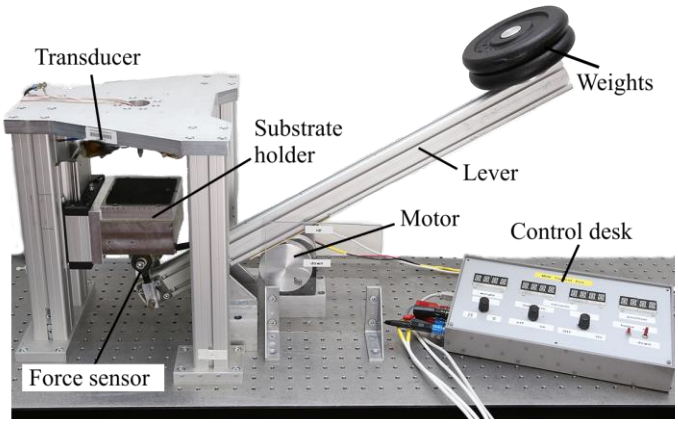

Fig. 1. Laboratory system for two-dimensional bonding

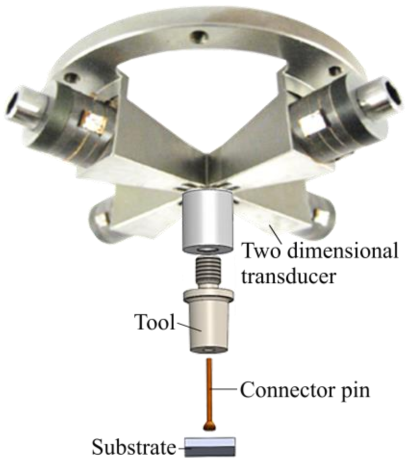

Fig. 2. Detailed view of the two-dimensional bonding system

III. Finite Element Analysis for Optimizing Normal-Pressure Distribution

Interrelations between micro weld formation and bond parameters as bond duration, ultrasonic voltage and normal force for copper bonding applications have been investigated in [7]. One major aspect of micro weld formation is a homogenous normal pressure distribution [4], yielding a homogenous activation of interconnection zone during bonding [1]. Achieving an as homogenous normal pressure distribution as possible, FEM was used to optimise the tool and pin geometry.

In analogy to tools used for one-dimensional bonding, different flank angles of the conical bond tool were analysed: A flank angle of 0 ° results in a flat contact of tool and work piece as also used in thin wire bonding, maximal angle used makes a contact comparable to a standard tool with a V-groove shaped tool-tip. Additionally, the bottom surface of the nail-like pin was made convex using a constant radius, which is in analogy to the wire diameter in wire bonding, but on a different scale (cf. Fig. 3).

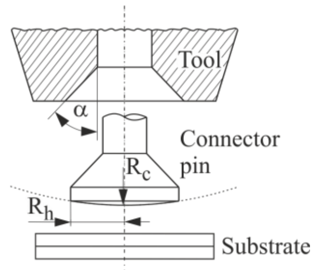

Fig. 3. Sectional view of the tool for bonding nail-like pins on copper plate.

Within [4] and [7] normal pressure distribution was identified for having the main impact on micro weld formation. Very high local normal pressure leads to stick between partial areas of work piece and substrate during bonding, which is unwanted as friction energy is needed to build the interconnection. In contrast, a considerable reduction of normal pressure distribution equally leads to reduction of induced energy within the contact zone, which seems to prevent micro weld formation as well. Thus, FEM simulation results were analysed using two limits of normal pressure. These two limits were set arbitrarily to 70 % and 90 % of maximal occurring normal pressure. All partial areas having a computed normal pressure in between these limits were summed up to evaluate which combinations of the convexity radius and the flank angle yield the biggest area. This voted for a conical flank and a large convexity radius (cf. Fig. 4).

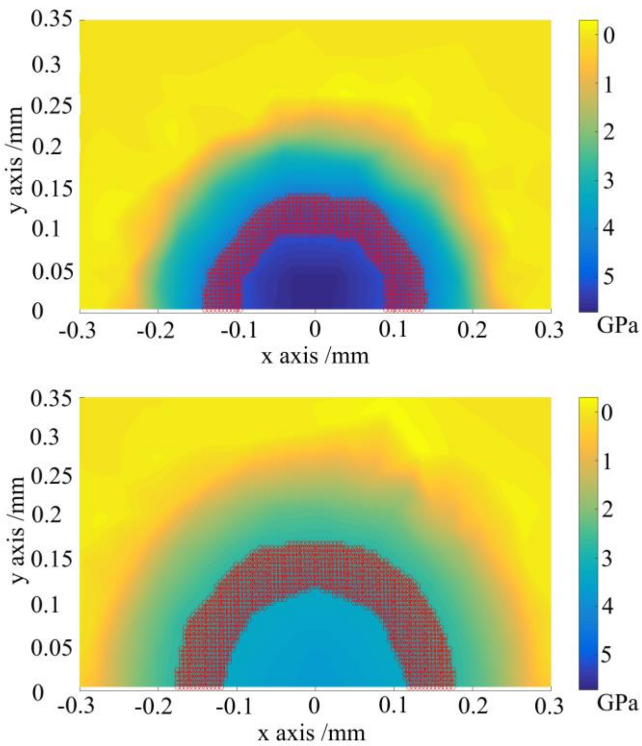

Fig. 4. Distribution of normal pressure in the contact between pin and copper plate (simulation result). Comparison between convexity radius with factor 1 (upper) and radius with factor 3 (bottom). Red region fulfilling criterion.

IV. DESIGN OF EXPERIMENTS AND DERIVATION OF STATISTICAL META-MODEL

To determine the influence of bond parameters on bond results like the shear force, experiments with variation of bond parameters were set up. Design of experiments was applied to find parameter combinations within considerable time and lowest possible effort. As usual for state-of-the-art one-dimensional wire bond processes, variation parameters are bond time, transducer voltage and normal force. To keep it simple, the ultrasonic voltage was set for one transducer only, while the second voltage was phase shifted and controlled to generate vibration at the same frequency and current amplitude, which resulted in a circular vibration of the tool tip. The impact of different trajectories on the bond result might be significant but will be reported later. Additional variation parameters were the copperplate material and the ultrasonic voltage of the second bond phase. In the following, the variation parameters are called “predictors” as commonly done in statistics. The parameter limits were estimated based on empirical values scaled up from heavy wire copper bonding applications and pre-studies according to [4].

The bond process was split into two equally long phases. Each phase consists of a 50 ms long ramp sub-phase and a constant voltage sub-phase. The constant voltage level of the second phase varied between 50 % and 80 % of the first constant voltage level. The weights applied for normal force generation were the same during the whole bond period, resulting in a constant normal force. The bond period set up with applied voltages and applied normal force is illustrated in Fig. 5. Two different substrate alloys (Cu-OF and CuSn6) were used to investigate their impact on bond strength and parameter space.

Shear force and the depth of the bond imprint are used as evaluation measures. These test results are called “responses” in the following and are indicators for the quality of bond connections. The purpose of the applied statistical evaluation is to get a meta-model describing the responses based on selected predictors, cf. Fig. 6. With this meta-model it is possible to predict responses with variation of predictors or seek predictors for achieving wanted response behaviour (bi-directionality).

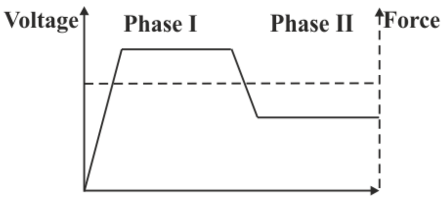

Fig. 5. Setup of bond process parameters

For gaining such a meta-model, the following steps were performed:

1. Checking measurement values for normal distribution (cf. Fig. 7)
2. Creation of regression model with tuning of parameters (combining linear, quadratic and interaction parameters, cf. TABLE I. , cf. TABLE II.)
3. Verification if parameter-transformation is necessary with the use of Box-Cox-plots (cf. Fig. 10)
4. Checking the distribution of residuals caused by application of meta-model (cf. Fig. 11)

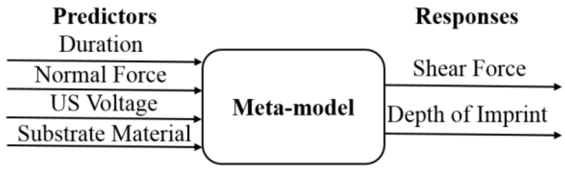

Fig. 6. Meta-model illustration showing meta-model with predictors and responses

The check for normal distribution of the measurement results, performed within step one, is a necessary step. Application of standard statistical models is valid only if measurements are normally distributed and independent. If the data are normal distributed, measurement values in a so-called normal probability plot (cf. Fig. 7) can be approximated by a straight line (logarithmic Gaussian function), which depicts the probability of each response value in a double-logarithmic diagram. The plot for shear force (cf. Fig. 7, top) shows that a majority of points are located close to this line. Deviations occurring at the edges are acceptable. In contrast, the plot for the depth of imprint shows that this response does not fulfil the criterion of normal distribution. The huge deviation indicates difficulties within the measurements. Consequently, the applicability of statistical meta-models for predicting bond imprint depth is not given.

Further investigation showed that the normal distribution is a result of variations in depth within the imprint. The measurement value is the deepest point of the residing profile within the substrate in reference to the substrate surface. As illustrated in Fig. 8, the deepest point within the surface profile sometimes results either from fractures arising from shearing of the pin (cf. Fig. 8, top) or, most importantly, from a rotation which is excited by the circular excitation trajectory of the bonding tool under specific combinations of the bond parameters (cf. Fig. 8, bottom). The rotation leads to some kind of drilling effect, leaving rotational scratches (cf. Fig. 9) and deep imprints, which are unwanted effects within this study and for bonding in general. The fractures arising from shearing, as mentioned above, cannot be influenced by a change of parameter setups, since they are a result of the shear force measurement. Furthermore, the rotation is a response and not a predictor. Consequently the derivation of a meta-model describing the depth of residing imprint (as response) with variation of selected bonding parameters (as predictors) seems rather ineffectual. To build an accurate meta-model describing the shear force, rotated and unrotated pins should be separated. Otherwise, shear forces being predicted based on a meta-model relying on all bonds will be inaccurate.

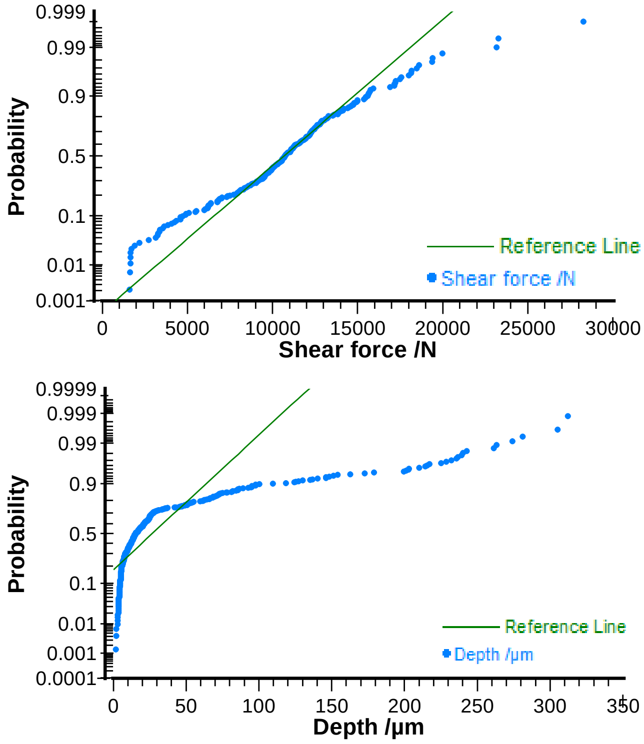

Fig. 7. Normal probability plots for shear force (top) and measured depth of imprint (bottom)

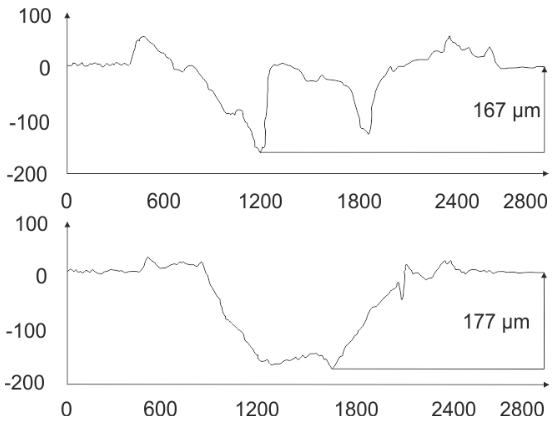

Fig. 8. Residing imprint of pin with cracks from shearing (top) and residing imprint of rotated pin (bottom)

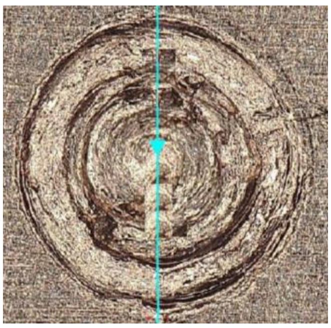

Fig. 9. Image of rotated imprint with scratch marks indicating rotation of nail-like pin

The subsequent step was the preparation of the meta-model describing the dependency of shear force on its predictors. Therefor all predictors ($X_{predictor}$) being considered were selected and added as combinations of linear, quadratic or interaction terms, each with a pre-factor (a, b, c, d) (cf. TABLE I.). Afterwards combinations of different parameters were used to build a meta-model for each valid response. The selection of parameters is based on the statistical significance of each predictor.

TABLE I. EXAMPLES FOR APPLICATION OF PREDICTORS WITHIN META-MODEL

Term type	Expression for predictor
Linear term	$a \times X_{predictor\ i}$
Quadratic term	$b \times X_{predictor\ i}^2$
Interaction term	$c \times X_{predictor\ i} \times X_{predictor\ k}$ $d \times X_{predictor\ i} \times X_{predictor\ k}^2$

$i \neq k$

The predictors of the meta-model for shear force are given in column one of TABLE II. In the second column, a likelihood measure, known as significance in statistics, is given for each predictor. The likelihood measure is "a measure of the likelihood that the apparent relationship between the response and a term … could happen by chance" [9]. The relationship of a predictor and the response is assumed to happen by chance, if the likelihood measure is equal to 1 and assumed to be systematic, if the likelihood measure is equal to 0. In general, terms having a likelihood value greater than 0.1 should not be considered. The only exception is that terms of higher order (quadratic or interaction terms) may only be included if all their parts of lower order are included. Terms higher order should only be included if they improve the adjusted r-square of the response.

The pre-factors a, b, c, d for each predictor using Cu-OF substrate material, are listed in column three of TABLE II. The meta-model pre-factors of CuSn6 material differentiate in all pre-factors containing the material predictor. At the bottom, a goodness factor ("Adj. R-Square") for the meta-model of shear force is given. The nearer the adj. r-square value tends to one, the more accurate the model is. Residuals generally account for deviation between the mathematical meta-model and measurement data. A meta-model consisting of fewer terms is more accurate than a meta-model with more terms. Thus, goal is to use as few terms as possible with increasing adjusted r-square.

The subsequent step was the verification of the necessity to transform response values. In statistics, this verification is done by the use of so called Box-Cox-plots. These Box-Cox-plots use different transformations applied to the response value and sum up the residuals squared for each resulting meta-model (with applied transformation). The sum of residuals squared for each transformed model are then plotted within one graph. Thus it is possible to evaluate if a transformation of the response led to a more accurate model (cf. Fig. 10), namely when the sum of the residuals of a transformed response is lower than that of the untransformed response. As can be seen in the Box-Cox-plot, no transformation improved the model. If the transformation improved the model, the untransformed value would be located above the 95% confidence interval line and the model improved by transformation would be below this line. Thus, no transformation was applied.

TABLE II. SUMMARY TABLE OF THE META-MODEL OF SHEAR FORCE, STATING EACH TERM'S SIGNIFICANCE VALUE IN EACH CELL AND A SUMMARY OF EACH MODEL'S GOODNESS

Predictor name	Coefficient	Likelihood measure
Constant	11815.70	0.1 e-10
Material	1056.79	1.5 e-04
Duration	1692.76	3.4 e-06
US1	1483.54	1.1 e-01
US2	618.75	3.5 e-01
Force	1019.24	8.8 e-06
Duration * Material	689.55	4.5 e-03
Material * US1	5821.42	6.8 e-10
Material * US2	-2661.95	2.8 e-05
Force * Material	-2391.99	0.1 e-10
Duration * US2	3700.19	1.3 e-09
US1 * US2	-4624.95	1.3 e-05
Adj. R-Square	0.54	

The next verification step to be performed before the meta-model could be used for interpretation was the verification of residual distribution. Within this step, residuals gained with application of the meta-model are plotted against variables, e.g. ascending/descending order of test runs or parameter set numbering. This plot then shows how much variation in accuracy the predictions have along the used variable, thus indicating if this variation is caused by systematic or rather random influences. Systematic influences have to be inhibited at any cost, since the impact of systematic errors contradicts the concept of statistical evaluation. As an example, shear force was determined by shearing the nail-head like pin with a chisel. The shear height, e.g. the height of the location where the chisel gets in contact with the nail-like pin has a major impact on the resulting shear force. Thus, if for some reason the height of the chisel was adjusted wrongly a certain day, a raise in residual plotted over time for the appropriate date could arise. This raise of residuals indicate that there is a systematic error with these measurements.

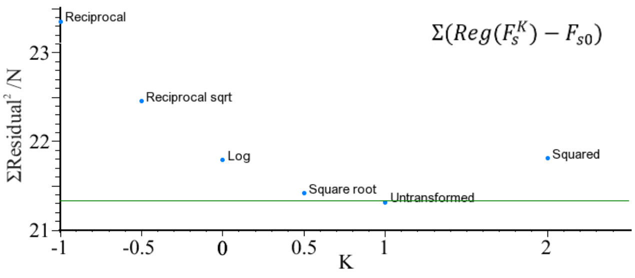

Fig. 10. Statistical Box-Cox-plot for shear force indicating that untransformed shear force measurements have the most accurate model. Green line illustrates 95% confidence interval of residual squared.

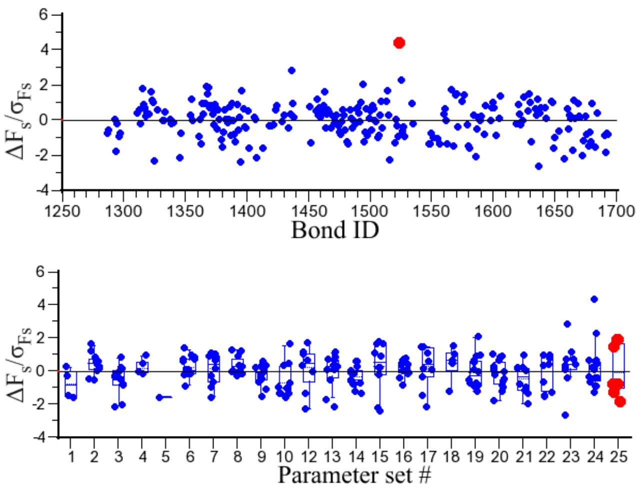

Fig. 11. Plot of residuals against variables for shear force. Upper plot showing residuals over continuous bond identification number (Bond ID), with one outlier bond (marked red, residual > 3 standard deviation). Lower plot showing residuals over parameter set number. Marked dots of parameter set 25 indicate a devision of residuals into groups of positive and negative residuals.

In Fig. 11, residuals of shear force have been plotted against continuous bond identification number as well as against the parameter set number. Measurements are accounted as outliers if their residual is greater than three standard deviations. Only one bond was determined as an outlier yielding a good quality of shear force measurements when looking at residuals over continuous bond id.

In contrast, looking at residuals plotted over parameter setups, setup 25 indicates a grouping of residuals. Each group of residuals are closely together, but both groups are either positive or negative, with large gap in between, even though the same parameter setup was used. This kind of grouping indicates that there is an additional parameter, not being accounted for within the previous evaluation. When these bonds were analysed more closely, it was identified that all bonds belonging to the group of negative residuals showed rotation of the pin (cf. Fig. 9), while no pins belonging to the group of positive residuals rotated.

One outcome of further research was that rotation of the bonded pin might show up as grouping, but does not do so necessarily. As long as no methods for identification of additional effects exist, meta-models relying on this data will be rather inaccurate for prediction of exact results as for example values of shear force.

The derived meta-model can be used to interpret the quantity of influence for each predictor on bond results. Therefore, so-called Effects Pareto plots are used for gaining more insights about how much each predictor of a statistical model effects the responses. In Fig. 12, showing the effects Pareto plot for shear force, all predictors influencing shear force are weighted using their quantity of influence on the response. One can see that shear force can be increased if the voltage during the first bond phase ("US1") is increased (first and sixths column; "material * US1" and "US1" respectively). Shear force is increased with increasing the duration and the voltage during the second bond phase ("US2") too (second, third, fifth column; "duration * US2", "material * US2" and "duration" respectively). On the contrary, high ultrasonic voltages during first and second bond phase considered together yield a decrease of resulting shear force (last column "US1 * US2").

The predictor "duration" of the meta-model always effects the duration of the first and the second bond phase. Additionally, all predictors containing "US2" increase the shear force, but not the last one ("US1 * US2"). Consequently, the shear force could be increased with matching the voltages of the first and the second phase, while decreasing the overall voltage level. This approach also results in a simplification of the bond setup, which then consists only of one period.

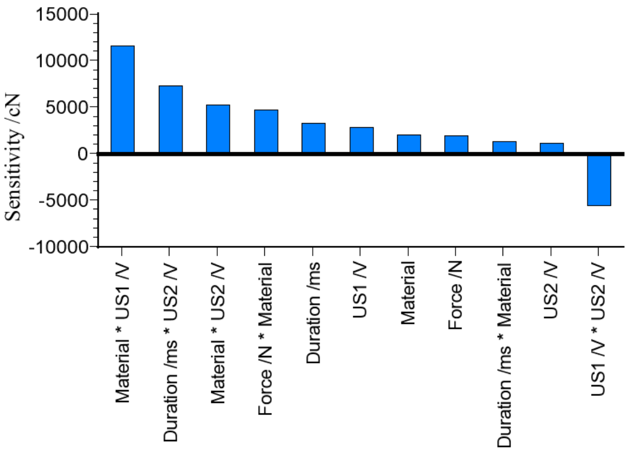

Fig. 12. Plot showing sensitivity of shear force on predictors.

V. CONCLUSION

Within this paper the development process of a two-dimensional vibration system with work piece and tool design was presented. Furthermore, the setup and the steps for experimental evaluation of the bond results were presented.

The following conclusions can be drawn from the presented tool and transducer design as well as from the statistical experimental evaluation:

(1) The two-dimensional trajectory approach is suited to bond work-pieces with an increased interconnection area sufficiently.

(2) Normal force distribution is optimised with adjusting flank angle as well as convexity radius of the nail-like pin.

(3) The ultrasonic voltage and the choice of material used for the substrate have the largest impact on the shear force.

(4) The bond process parameter setup can be simplified while maintaining high shear forces. Therefore, the ultrasonic voltage amplitudes of the first and the second phase have to be matched to the same, slightly decreased level. At the same time, an increased normal force can compensate the loss in frictional energy resulting from the decreased overall voltage level.

(5) Depending on bond parameter setups additional effects as rotation of the nail-like pin occur. The relationship between bond parameters and the rotational effect need to be studied further.

VI. ACKNOWLEDGMENT

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

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