Multi-dimensional Ultrasonic Copper Bonding – New Challenges for Tool Design

Paul Eichwald[1], Simon Althoff[1], Reinhard Schemmel[1], Walter Sextro[1],
Andreas Unger[2], Michael Brökelmann[2], Matthias Hunstig[2]

[1] University of Paderborn
Pohlweg 47-49
33098 Paderborn, Germany

[2] Hesse GmbH
Lise-Meitner-Str. 5
33104 Paderborn, Germany

Ph: +49(5251)601817; Fax: +49(5251)601803
Email: paul.eichwald@uni-paderborn.de

Abstract

In power electronics, copper connector pins are e.g. used to connect control boards with power modules. The new chip generation based on SiC and GaN technology increase the power density of semiconductor modules significantly with junction temperatures reaching 200°C. To enable reliable operation at such high temperature, the soldering of these connector pins should be substituted by a multi-dimensional copper-copper bonding technology. A copper pin welded directly on DBC substrate also simplifies the assembly. With this aim, a proper bond tool and a suitable connector pin geometry are designed. This paper presents a two-dimensional trajectory approach for ultrasonic bonding of copper pieces, e.g. connector pins, with the intention to minimize mechanical stresses exposed to the substrate. This is achieved using a multi-dimensional vibration system with multiple transducers known from flip chip bonding. Applying a planar relative motion between the bonding piece and the substrate increases the induced frictional power compared to one-dimensional excitation.

The core of this work is the development of a new tool design which enables a reliable and effective transmission of the multidimensional vibration into the contact area between nail-shaped bonding piece and substrate. For this purpose, different bonding tool as well as bonding piece designs are discussed. A proper bonding tool design is selected based on the simulated alternatives. This tool is examined in bonding experiments and the results are presented. In addition, different grades of hardness for bonding piece and substrate are examined as well as different bonding parameters. Optical inspection of the bonded area shows the emergence of initial micro welds in form of a ring which is growing in direction of the interface boundaries with increasing bonding duration.

Key words

Ultrasonic bonding, copper bonding, multidimensional transducer, tool design, finite element simulation

I. Introduction

Copper connector pins are e.g. used to connect control boards with power modules. These connector pins can be molded in housings and are afterwards wire bonded or directly joined to the direct bonded copper (DBC). In case of directly connecting the pins, state-of-the-art technology is to solder sleeves to the DBC. The connector pins are pressed into these sleeves and thus fixed to be ready for mounting the control board (cf.fig.1). This type of connection is no more qualified for usage along with the new generation of power semiconductors based on SiC and GaN technology. Due to increased power density and elevated junction temperatures of up to 200°C. At such temperatures the soldering should be substituted by high power ultrasonic bonding of copper-copper pin connection. Therefore, a proper bond tool and suitable connector pin geometry have to be designed. Such a tool has to fulfill various functional requirements named in [1], [2] and [5]:

- Fix the connector pin while the vibration system moves to the bond location.
- Avoid damages at the connector pin.
- Clamping the connector pin during planar motion.
- Apply normal force for uniform contact conditions, i.e. homogeneous pressure distribution.
- Avoid tool/substrate contact during bonding to prevent substrate damage.
- Meet the acoustic demands of the vibration system, e.g. resonance frequency and required vibration amplitude.

Furthermore, the assembly of pin and sleeve has to be replaced by a newly designed connector pin for the new process. The design of the upper section of the connector pin has to be maintained to fulfill the requirements of electrical contact to the control board (Pressfit). The lower part resembles the nail-shaped design of the sleeve which provides a supporting surface for the bonding tool and ensures a sufficient contact area to the substrate. There are various possibilities to design the upper side of the pin foot (contact pin-tool) and the lower side (contact substrate-pin). The upper side can be complementary to the tool shape. Flat, conical and convex designs are conceivable for both upper and lower side (red box in fig. 1).

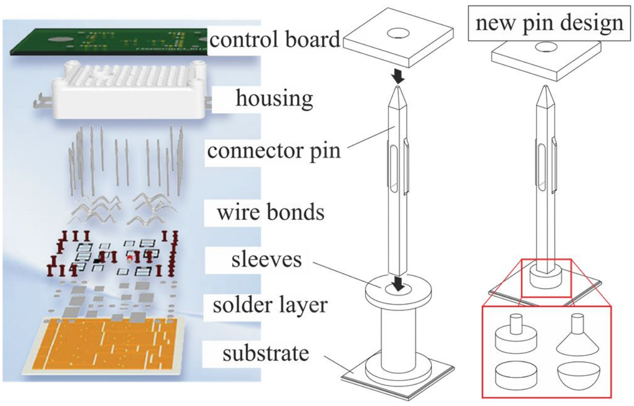

Fig. 1: Assembly of a power module with pressfit contact between connector pin and control board using the current pin/sleeve compound and conceivable designs of the connector pin for ultrasonic bonding

II. Ultrasonic bonding of connector pin

In the first step the frictional energy to bond a copper connector pin is estimated from heavy copper wire bonding assuming one-dimensional excitation. A relative velocity of $v_r = 1{,}6$ m/s and a normal load of $F_N = 30$ N are measured during 500 µm copper wire bonding [4]. It is assumed that the expansion of bonded area between two contacting surfaces during ultrasonic bonding is proportional to the frictional power

$$P_R = \mu \cdot F_N \cdot v_r \ , \qquad (1)$$

where µ is the friction coefficient of the contact pair, F_N is the load in normal direction of the surface, v_r the relative velocity between the contact partners [6]. Assuming that the frictional power should increase proportionally with the area to weld, the induced frictional power has to be upscaled by factor 10 for the connector pin in comparison to the 500µm copper wire bonding process. It was decided to increase the velocity by a factor of 2 to limit dynamical stress in the transducer. Consequently, the normal force has to be raised by a factor of 5. Due to the contact area expansion, this results in a reduction of the average substrate pressure compared to wire bonding.

Multidimensional Approach

A new vibration system needs to be developed, because a simple upscaling of bonding parameters using currently available ultrasonic wire/ribbon bonding machines is hardly possible, due to limited power and possible substrate damage. Therefore, a two-dimensional trajectory approach for ultrasonic copper bonding is chosen with the intention to bond copper bonding pieces, e.g. connector pins without raising the static stress occurring in the substrate compared to heavy wire bonding. This is achieved by using a multi-dimensional vibration system known from flip chip bonding (fig. 2) for the first tests, which has already been described in [10] and [11]. It was suggested in [7] to apply planar relative motion, e.g. a circular trajectory, between the bonding piece and the substrate to increases the induced frictional power. It was concluded that the frictional power is increased by a factor of 1.57 using a circular trajectory compared to one-dimensional excitation

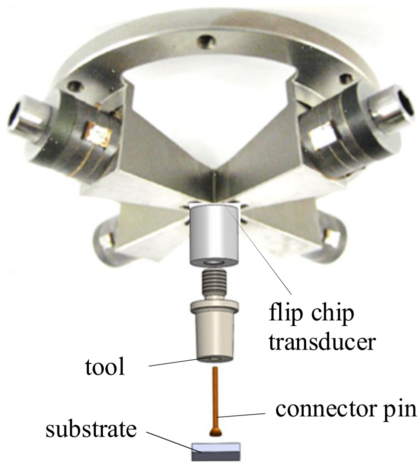

Fig. 2: Exploded view of multidimensional vibration system

with the same amplitude and frequency. Furthermore, stick-slip effects due to face turning points described in [3] between bonding piece and substrate resulting in a loss of friction power are avoided.

III. Finite element modeling of multi-dimensional ultrasonic bonding

A new multi-dimensional bonding system for connector pins was designed by the help of finite element method using ANSYS. Knowledge from wire bonding, e.g. about ultrasonic material softening, is taken into account in the finite element simulation. The design process was split in two phases due to usage of different simulation types. First, a harmonic analysis of the tool/pin/substrate assembly is done to design a tool which fulfills the acoustic demands. In the next step a static mechanical analysis is performed to design the contact section to evaluate the mechanical coupling between tool and connector pin for the multi-dimensional motion.

Harmonic design

The tool is an important component within the vibration system which guides the vibrations from the transducer to the connector pin. It has to fulfill several acoustic demands using the described flip chip transducer which have to be considered during harmonic design:

- Eigenfrequency at approx. 62 kHz, matching the operation frequency of the used flip chip transducer to achieve the highest level of electrical efficiency.
- Maximum oscillation amplitude at the tool tip.
- Bending mode with uniform deflection in all directions to perform circular motion in the working plane which increases the induced frictional power compared to one-dimensional excitation.

The harmonic analysis was performed applying a normal force of $F_y = 150$ N (bonding force) on the vibration system to take pre-stress into account and consequently a potential change of eigenmodes. A multi-dimensional excitation is performed by applying forces in x- and z-direction. F_x and F_z oscillate harmoniously with a relative phase of 90°, which is depicted in

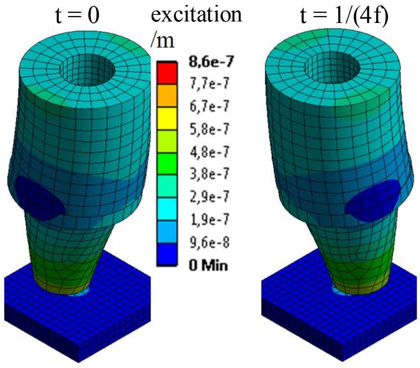

Fig. 3: Pre-stressed vibration system with oscillating forces F_x and F_z

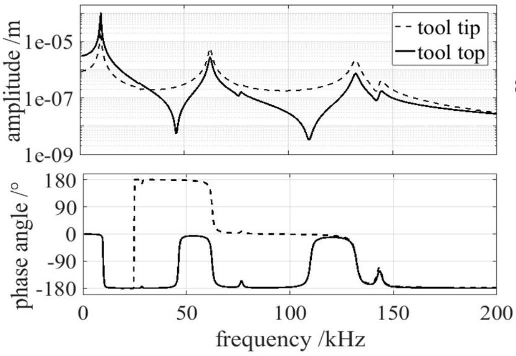

Fig. 4: Frequency response at topside of the tool as well as tool tip

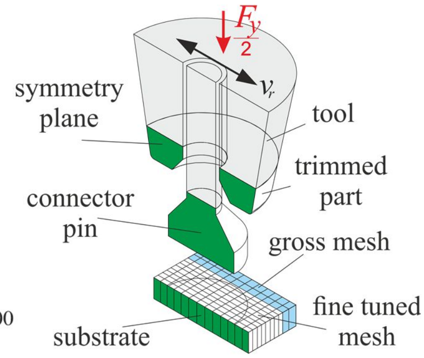

Fig. 5: FE model of ultrasonic bonding of connector pin

fig. 3. The amplitudes of the oscillating forces $\widehat{F_x}$ and $\widehat{F_z}$ are determined assuming the maximum applicable tangential force in case of an unbonded pin as $F_{T,max} = \mu_{PS} * F_y = 0.3 * 150\,N = 45\,N$, with the coefficient of friction μ_{PS} between connector pin and substrate at the beginning of the process [5]. Fig. 3 illustrates two snapshots of the selected tool design for maximum tool tip excitation in *x*- and *z*- direction. It shows a bending mode with a uniform deflection for circular motion at the eigenfrequency at 62 kHz, which is shown in the frequency response in fig 4.

Modelling contact section tool/pin

A 3D finite element model of bond tool, connector pin and substrate, which is depicted in fig. 5, was created using ANSYS. Due to symmetric geometry along the vertical plane, a half model was sufficient in the FE model. The mesh is refined in the contact area to get more detailed results in the contact area, e.g. the contact pressure. Remaining areas are meshed with a coarse mesh. These adoptions are reducing the computing time due to the reduced number of elements and nodes. The vertical displacement is determined by considering the softening of the copper pin as described in [5]. Constant normal force is applied on the topside of the tool. The stress-strain relation of the copper pin is adapted within the simulation to conform to the vertical pin deformation estimated from the wire bonding process. Subsequently, the tool is excited in the tangential direction. A vibration amplitude of 5 µm was chosen for this tangential deflection of the tool, which was measured by the help of laser vibrometry for copper wire bonding [2]. The coefficient of friction between tool and pin is set to 0.37 and between pin and substrate to 0.3 [5]. The normal force F_y is set to 150 N.

Tangential force transmission

The geometry of the bonding tool has a major influence on the transmission of the tangential excitation into relative motion in the contact area between connector pin and substrate. Due to the rotational symmetry of tool and pin, the force transmission is assumed to be similar in all directions of the working plane. Therefore, the tool was just excited in one direction with an amplitude of 5 µm. Two tool designs are chosen to illustrate how the tangential force is transmitted. Fig. 6 illustrates the examined tool/pin design in case of flat (a) and conical (b) tool shape. Furthermore, fig. 6 depicts the corresponding tangential force-displacement curve for both designs in case of initial non-softened (continuous line in fig. 6) pin material as well as for the final softening status of USS=0.3 (dashed line in fig. 6) as suggested in [5]. Using the conical tool an up to 25% higher tangential force can be transmitted compared to a flat tool. The gap between both designs even widens up to 35% for high softening status. The conical form fit is preventing the tool from gross slippage at the top of the connector pin due to high clamping force as already described in [5]. Thus, the tangential motion is transmitted mainly via form fit, not force fit. In contrast, the flat tool transmits the tangential force via friction. A further advantage of the cone is the feature of self-centering the connector pin to prevent tilting. Due to these advantages, a conical tool is used for the investigations described in the following.

Pressure distribution

The pressure distribution between pin and substrate has a high impact on the welding result. Parts of the contact are sliding and parts are sticking, due to non-homogeneous pressure distribution which was also described in [4] and [5] for copper wire bonding. Fig. 8 depicts the pressure distribution in the contact between connector pin and substrate. Due to connector pin softening, the contact surface is increasing and consequently the pressure distribution widens while the maximum amount of pressure decreases in case of constant bonding force. The pressure distribution is circular with a minimum in the center of the contact for a non-softened pin.
In case of a conical tool shape the pressure distribution is relatively homogeneous and varies between $9.8 * 10^7$ Pa and $1.2 * 10^8$ Pa which leads to an almost completely green contact surface using the shown color scale. The ring-shaped pressure distribution becomes more distinct in case of a softened pin using a flat tool and can be explained by flow of force represented via von-Mises stress in cross-sectional area of the pin (cf. fig 6. (a) and (b)). Furthermore, using a conical tool the scope of pressure widens and the ring-shaped distribution can be observed in this case (softened pin). One reason is the hole in the tool center, which captures the connector pin neck. The bonding normal force is being redirected via the pin due to angular force application from tool to pin. Consequently, the pressure distribution becomes more homogeneous for the

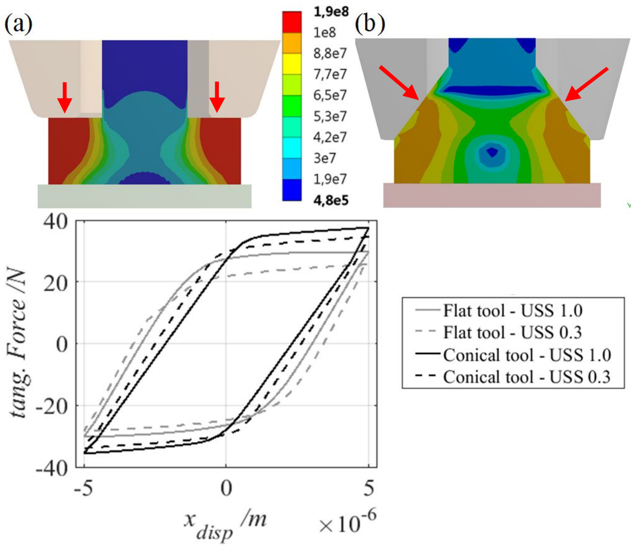

Fig. 6: Von-Mises stress and tangential force-displacement diagram for different softening states of the pin in case of flat (a) and conical (b) tool shape

softened pin material which is advantageous for the bonding performance. The simplified assumption of one-directional excitation results in spots of pressure in case of softened pin.

Plasticizing of connector pin

The natural oxide-layers of copper material of the bonding partners pin and substrate have an influence on the bond quality [12]. It is well known, that in wire bonding a high plastic strain in the contact zone due to material softening has a positive effect on surface cleaning and consequently on surface activation [14]. High contact pressure leads to high plastic strain. Flat as well as convex shape on the bottom side of the pin head were chosen to investigate the difference in equivalent plastic strain at the end of bonding (softened pin) which is depicted in fig. 7. The flat pin shape is complementary to the flat substrate surface which leads to rather low plastic strain. Furthermore, a ring shaped plasticity zone can be recognized due to the already described pressure distribution. In case of a convex pin shape, a high amount of pressure is observed at the beginning of bond formation due to the small contact area. In the ongoing process, the convex shape is flattened and high plastic strain occur.

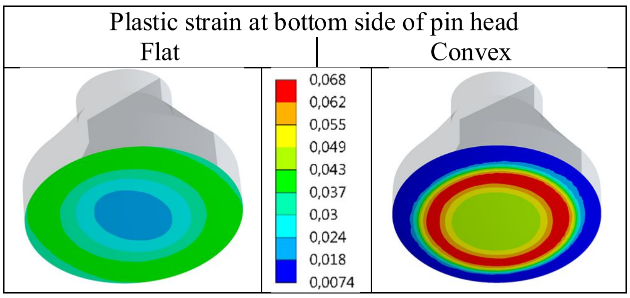

Fig. 7: Plastic strain at bottom side of pin head in case of flat and convex shape

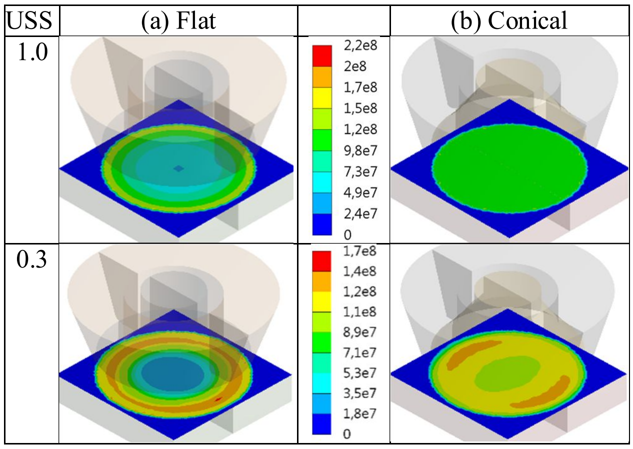

Fig. 8: Pressure distribution between pin and substrate for different ultrasonic softening states of the pin in case of flat (a) and conical (b) tool shape

The applied normal load is not sufficient to completely flatten the convex shape (dark blue ellipse in fig. 7). It can be concluded, that the chosen convexity is too pronounced for the softening behavior. Nevertheless, a convex pin shape seems to be beneficial for ultrasonic bonding due to its plastic strain behavior.

IV. Experimental investigation and results

Bond tests were done using a multi-dimensional vibration system. To validate the finite element design, a rotationally symmetric prototype tool manufactured out of steel. The connector pin was manufactured from CuSn6. Due to promising results a conical shape at the upper side and a convex shape at the bottom side of pin head were chosen. Due to the prototype setup the normal force was applied via pre-stressing the multi-dimensional vibration system and is not controlled. Therefore, the normal load decreases as a result of the ultrasonic softening of pin and substrate during the bonding process.

Properties of the vibration system

The vibration system (transducer, tool) was measured electrically under freely oscillating conditions. Fig. 9 (r.) shows the measured frequency response of the electrical admittance for the perpendicular transducer #1 and #2. They show resonances at 60.5 kHz (#1) and 60.1 kHz (#2). Mechanical coupling between the two transducers results in smaller admittance peaks at the resonance frequency of the respective other transducer.

Laser measurements

To estimate the tool tip trajectory at an excitement frequency of approx. 61 kHz, the motion in the working plane was measured with two orthogonal laser vibrometers as shown in fig. 9 (l.). The trajectory in the working plane at different working times is shown in fig. 10 for free oscillation (a) and under bonding conditions (b). In both configurations a circular trajectory was measured. The applied transducer current was

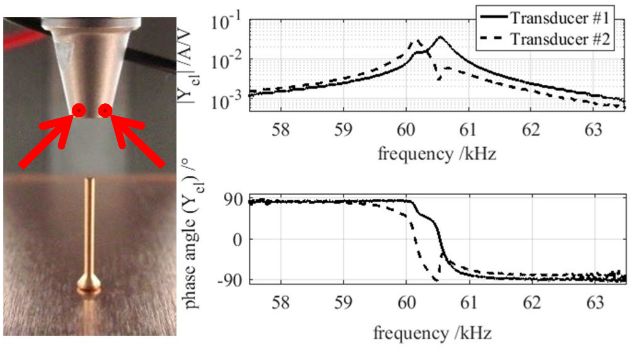

Fig. 9: (l.) Measurement points at the tool (r.) Frequency response of the electrical admittance

halved for the free oscillating system in comparison to the case of bonding to prevent mechanical overload. The increase of the vibration amplitude under bonding conditions can be attributed to a decrease of normal load during the bonding process in this first test setup.

Shear tests and inspection of shear area

Bonding test are conducted using a demonstrator system by varying the hardness of pin and substrate as well as the bonding time. At each parameter set 10 bonding results are taken into account on average. The Vickers hardness of the used materials is listed in table I. The used connector pin (CuSn6) has a hardness of 310 HV. The pin was soft annealed to lower the hardness down to 106 HV. Annealing was conducted in vacuum to avoid high-temperature oxidation. Substrate (Cu) with 90 HV (soft) and 200 HV (hard) was chosen. Fig. 11 (a) illustrates the shear test results for the different material hardness pairings. Shear forces rise up to 240 N. It can be observed that a hard connector pin on hard substrate is not beneficial for multi-dimensional bonding. One reason can be the low ultrasonic softening and consequently low vertical deformation of the bottom side of the convex pin, which leads to low contact area with high pressure. Additionally, fig. 11 (a) illustrates that at least one contact partner should be soft. High shear force can be reached in bonding a soft connector pin on hard substrate. Nevertheless, the scattering of shear force is still high in comparison to a soft substrate material. Bases on these preliminary results, it can be concluded that the highest amount of shear force and additionally low standard deviation can be reached in ultrasonic bonding a soft connector pin on soft substrate. Fig. 11 (b) depicts the variation in bonding duration. Bonding duration of 300 ms seems to be not enough for reliable welds which can be observed in the high scattering. It can be concluded that the optimum bond duration is approximately 600 ms using the described vibration system. Increasing the bonding time up to 1000 ms increases the standard deviation and shear forces up to 240 N can be reached.

Table I: Material properties of the frictional partners

	Substrate (Cu)		Connector pin (CuSn6)	
	soft	hard	soft	hard
Hardness (Vickers)	90 HV	200 HV	106 HV	310 HV

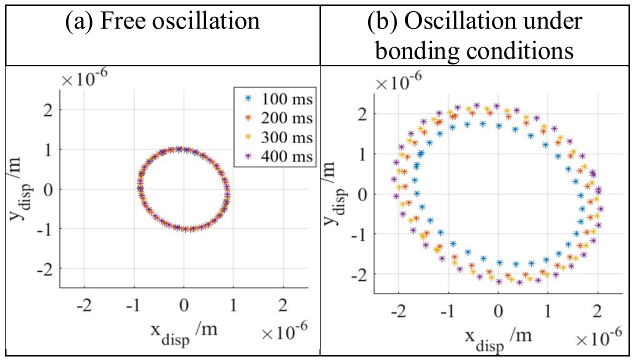

Fig. 10: Vibration amplitude in bonding plane at tool tip in case of (a) free oscillation and (b) bonding

Moreover, the corresponding shear area was determined using a microscope. Fig. 12 illustrates the shear areas of pin bottom side as well as the corresponding substrate surface for both designs in case of a hard pin bonded on soft substrate. To examine the influence of bottom side design of the pin head, a flat as well as a convex shape were tested. The illustrated pins were bonded with a normal load of 145 N. Bonding duration was 300 ms. It is assumed that the grey section is the friction area (circled in red in fig. 12), formed by relative motion between the contact partner. In contrast to the flat pin, the convex pin was not completely in contact with the substrate. One explanation is the low pressure which is not sufficient to deform the convex surface. Another reason is a low softening of the material due to insufficient ultrasonic power. Inspection of the bonded area evinces the emergence of initial micro welds in form of a ring, which is growing in direction of the interface boundaries with increasing bonding duration. Such welding patterns are often observed in wire bonding [6, 13].

I. Conclusion

This paper presents a two-dimensional trajectory approach for ultrasonic copper bonding with the intention to bond copper connector pins without highly increasing mechanical stress (normal stress, shear stresses etc.) in the substrate compared to heavy wire bonding.

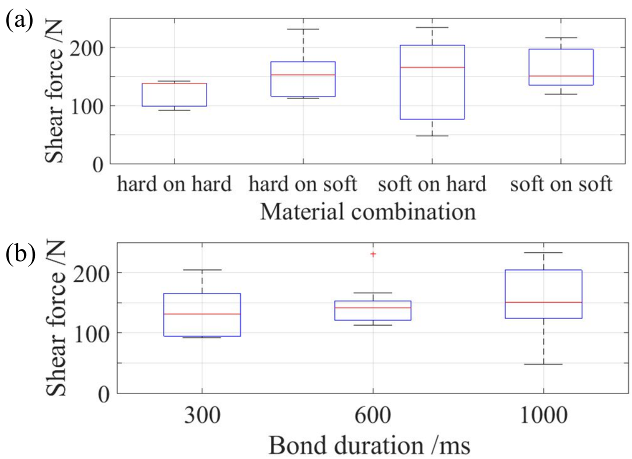

Fig. 11: Shear force for different (a) material hardness combination (b) bond duration

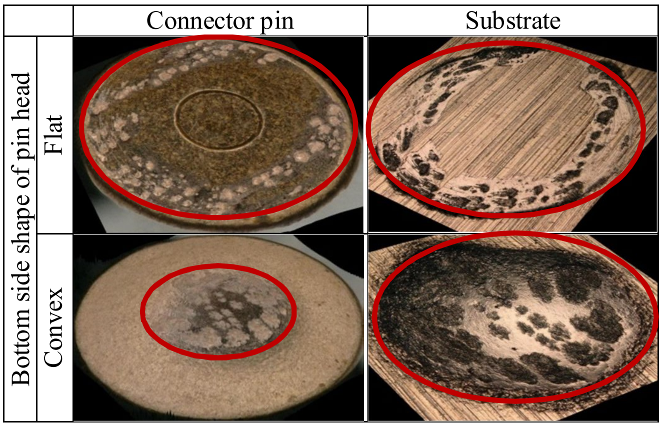

Fig. 12: Shear surface of connector pin and substrate for flat and convex pin design

This is achieved by designing a multi-dimensional vibration system known from flip chip bonding. The induced frictional energy has to be raised according to the increase in bond area compared to the wire bonding process. A new, rotationally symmetric tool design is essential due to the two-dimensional excitation. First of all, a harmonic analysis of the tool/pin/substrate assembly was done to design a tool which fulfills the acoustic demands. The tool resonance frequency can be adapted by varying the tool length accordingly. A tapering at the tool adapts the deflection amplitude at tool tip.

In the next step, the contact shape between tool and topside of the pin head is designed. The tool/pin contact area has an essential influence on the maximum transmittable tangential force as well as on the pressure distribution in the welding zone (pin/substrate), which affects the bond quality. The pin head allows to conceive a complementary design of the contacting surfaces of the tool and the topside of the pin head. Thus, loss in energy due to plastic deformation at the pin topside is prevented in comparison to wire bonding. A conical tool shape prevents gross slippage between tool and pin in comparison to a flat tool design and results in higher transmittable tangential force. It also leads to a more homogenous pressure distribution. The convex shape of the bottom side of the pin head shows further potential for optimization. The induced power was insufficient to flatten the convexity of bottom side of pin head, which results in a reduced contact surface between pin and substrate.

The findings from the finite element simulation were verified by measuring the tool tip trajectory using a laser vibrometer. Bonding tests for different hardness of connector pin and substrate show shear forces up to 240 N. It can be concluded that an ultrasonic system with more power has to be designed in order to reach even higher bond strength. With this system, it should be possible to reduce the optimal bonding time to a duration known from wire bonding.

Summing up, the newly designed capillary tool for nail-shaped bonding pieces works properly in terms of resonance frequency and vibration amplitude. The functioning of the tool in regards of clamping and force transition is proven. The two-dimensional high power bonding process shows promising bonding results.

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