

Using complex multi-dimensional vibration trajectories in ultrasonic bonding and welding

Reinhard Schemmel^a, Tobias Hemsel^a, Collin Dymel^a, Matthias Hunstig^b, Michael Brökelmann^b, Walter Sextro^a

^aChair of Dynamics and Mechatronics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

^bHesse GmbH, Lise-Meitner-Straße 5, 33104 Paderborn, Germany

Abstract

Ultrasonic joining is a common industrial process. In the electronics industry it is used to form electrical connections, including those of dissimilar materials. Multiple influencing factors in ultrasonic joining are known and extensively investigated; process parameters like ultrasonic power, bond force, and bonding frequency of the ultrasonic vibration are known to have a high impact on a reliable joining process and need to be adapted for each new application with different geometry or materials. This contribution is focused on increasing ultrasonic power transmitted to the interface and keeping mechanical stresses during ultrasonic bonding low by using a multi-dimensional ultrasonic transducer concept. Bonding results for a new designed connector pin in IGBT-modules achieved by multi- and one-dimensional bonding are discussed.

Keywords: ultrasonic bonding, ultrasonic welding, multi-dimensional bonding, complex vibration, multi-frequent, two-dimensional friction model

1. Introduction

Since about 1954 an abrupt change of the joining technique in microelectronics occurred when the mesa transistor was developed which lead to a significantly decreased size of the contact areas and new joining processes were developed to create reliable electrical connections; in 1960 Sonobond received the first patent for ultrasonic metal welding, [1]. The ultrasonic joining technique was then further developed and is used in various applications these days. Ultrasonic bonding is a solid-state joining process, where the induced oscillating shear between the faying surfaces is mainly responsible for the metallurgical bond formation. During bond formation, different processes take place, thus the bond process is typically divided into different phases, [2, 3], see **Figure 1**.

In the first phase (Pre-Deformation Phase) a static touchdown force F_{TD} is applied to the workpiece. The workpiece is clamped by the bond tool (wedge) at the bond position and an initial contact area is created, [4].

In the next phase (Cleaning Phase), the ultrasonic vibration x_W and the bond normal force F_{bn} , which can differ from F_{TD} , are applied to the workpiece. When the induced oscillating shear forces are large enough to overcome the sticking-force between the workpiece and substrate, sliding occurs. The oxide layers and other contaminations are then detached from the faying surfaces and are transported to the peripheral contact region, [5, 6].

In the third phase (Deformation Phase), high plastic deformation of the workpiece and the interface region of the

substrate can be seen, even though the normal force F_{bn} is not increased significantly; the effect of high deformation under influence of ultrasonic vibration is known as the Ultrasonic Softening Effect, [7]. During the Deformation Phase, the contact roughness is reduced and thus the real contact area is increased; the reduction of the gap between the two faying surfaces is crucial for the intermetallic bond formation, [8]. Additionally first micro-junctions occur in areas, where contact asperities are plastically deformed, [9].

In the last phase (Interdiffusion Phase), material flow between workpiece and substrate can be seen. The material flow occurs without melting the materials and is induced by the oscillating shear stress and plastic strain in the interface, [10]. The material flow leads to an intermetallic connection between workpiece and substrate; the two metals are not molten, thus dissimilar metals with different melting temperatures can be bonded, [11, 12, 13].

Depending on the application and the workpieces that can vary in contact area size and material, ultrasonic joining is divided into fine and heavy wire bonding, ribbon bonding, and ultrasonic welding, **Table 1**. Fine wire bonding is used for low-current connections in devices like lead-frame packages, small sensors or antenna designs for CMOS wafers where the antenna is designed by the loop of the wire bond, [14, 15]. In high frequency applications fine ribbon bonding is used to reduce the cross section and thereby the self induction of the workpiece at high switching frequencies (skin effect), [16]. In heavy wire bonding, larger wire diameters compared to fine wire bonding are used to connect electrical devices like insulated-gate bipo-

URL: reinhard.schemmel@upb.de (Reinhard Schemmel)

Table 1: Comparison of the different process technologies in ultrasonic joining by the size of the workpiece, typical workpiece materials, and equipment used in ultrasonic bonding and welding. For wires the diameter, for ribbons and stranded wires the cross section of the workpieces are given. For metal spot welding the welded contact and the sheet thickness are given.

Technology	Size	Typical Material	Equipment (Power/Frequency)
Fine wire bonding (wedge-wedge)	Diameter 12.5-75 μm	AlSi1, AlMg, Au, Ag, Cu, Pt	Bonding machine (2W/60-140 kHz) with fine wire/ribbon bond head
Fine ribbon bonding	Cross section 6x35-25x250 μm^2		
Heavy wire bonding	Diameter 50-600 μm	Al, Cu, Al-clad Cu	Bonding machine (50-200 W / 40-100 kHz) with heavy wire/ribbon bond head
Heavy ribbon bonding	Cross section 25x250-400x2000 μm^2		
Ultrasonic metal spot welding	Contact area 0.3-100 mm^2 Sheet thickness up to 5 mm	Cu, CuFe2P, CuSn6, CuNiSi	Welding press (0.5-10 kW/20-40 kHz)
Ultrasonic welding of stranded wires	Cross section 0.26-60 mm^2	Cu	

in AEC-Q100 and Q101, [25]; e.g. the grade 1 standard defines 1000 cycles in the range $-55\text{ }^\circ\text{C}/+150\text{ }^\circ\text{C}$. Especially solder joints fail under these harsh test conditions and new solder alloys need to be developed. Ultrasonically bonded connections on the other hand - with higher mechanical strength of the intermetallic bond connection - show higher reliability under these conditions. Thus substitution of solder joints by ultrasonically bonded connections can increase the reliability of electrical devices in the future.

In this contribution, the impact of the multi-dimensional vibration parameters like the bonding frequency and the shapes of the different vibration loci on the bond formation are summarized in the current state of science. A multi-dimensional ultrasonic transducer concept with mono- and multi-frequent planar oscillation loci and its control concept is presented. For validation of the multi-dimensional transducer, vibration trajectories of the ultrasonic bonding tool under loaded conditions during ultrasonic bonding are shown. For a profound understanding of the impact of the planar multi-frequent vibration trajectories on the bond formation, simulation results of a parameter sweep with a two-dimensional friction model are analyzed. In addition to the numerical investigations, bonding experiments for a new connector pin design for IGBT modules are utilized to evaluate the bond quality for one- and two-dimensional ultrasonic bonding.

2. Impact of the bonding frequency and direction

2.1. Background: Bonding frequency

In the past, several approaches for investigating the impact of different bonding frequencies have been reported,

Onuki et.al. reported in [27] that bonding aluminum wires with 500 μm diameter on 5 μm thick AlSi films on transistor chips with 110 kHz raises the bond strength and decreases the deformation of the Al-wire compared to 60 kHz. Chan et.al. found in [28] for bonding Au-wires with 25.4 μm diameter on a PCB bond pad with two bonding frequencies at 62 kHz and 138 kHz that bonding with 138 kHz leads to a larger bond process window (bond pad temperature and ultrasonic power). In contrast to the results in [28], Charles et.al. reported in [29] and [30] for bonding Au-wire with 25.4 μm diameter, bonding frequencies of 60 kHz and 100 kHz, three different substrate metallizations, and three different test patterns that the benefits of the different bonding frequencies were dependent on the metallization and a larger process window for 60 kHz compared to 100 kHz was observed.

Heinen et.al. reported in [31] for bonding on integrated circuits (ICs) with assembled test chips on a polymeric dielectric that bonding with a frequency twice as high than 60 kHz provides additional process reliability and a larger process window. The high bonding frequencies provided more focused ultrasonic energy that does not penetrate as deeply into the chip and on pads on soft polymers such as Teflon or unreinforced polyimide the bonding quality is improved with higher frequency.

Schemmel et.al. reported in [32] for bonding on substrate substructures with resonance frequencies near the bonding frequency of the transducer, that a higher bonding frequency than the resonance frequency of the substructure is beneficial to reduce substrate vibration amplitudes during the bond process. This effect was explained by the absorbing character of mechanical systems when being excited with frequencies higher than their resonance frequency.

2.2. Background: Multi-dimensional bonding

In ultrasonic joining, one-dimensional translatory motion welding systems are most established. As an alternative welding system, multi-dimensional ultrasonic bonding has been investigated by several different researchers, [33]-[41]. Asami et.al. reported in [34] that the one-dimensional translatory motion of the transducer leads to directional bond quality characteristics of the contact area. Contradictory, Hetrick et.al. reported in [35] that no directionality was found for ultrasonic welding with a one-dimensional ultrasonic welding system.

Asami et.al. presented in [36] a multi-dimensional vibration system with a one-dimensional translatory vibration and additional torsional movement of the transducer-horn; bonding experiments showed that a multi-dimensional vibration locus increases the weld quality significantly compared to the one-dimensional welding process at the same electric input power. Multi-frequency bonding tests with two-dimensional vibration locus at 18.3 kHz and 29.3 kHz were performed in welding dissimilar metals (Al and Cu plates) by Asami et.al. and Tamada et.al. in [37, 38, 39]. It was found, that using a non-directional vibration locus (ratio between the two vibration amplitudes 1:1) produced the highest weld strength.

Dymel et.al. presented a versatile test rig for multi-dimensional ultrasonic bonding of connector pins of a semiconductor module in [40]. The shear force values were evaluated depending on the ratio of the two vibration amplitudes; by increasing the ratio to one (circle locus) the shear force value was increased by a factor of 3.22 compared to one-dimensional bonding. Dymel et.al. also reported in [41], that a circular ultrasonic excitation of the rotationally symmetrical connector pin can lead to a rotation of the pin itself.

3. Multidimensional transducer concept

The concept of the multi-dimensional ultrasonic transducer is shown in **Figure 2**. Four single transducers are mounted to a coupling element in the center and are oriented perpendicular to each other. In the center of the coupling element the ultrasonic bonding tool is mounted. The pairs of transducers opposing each other are moving in the same direction and are called "channels" in the following; the channels are operated by excitation voltages $U_1(t)$ and $U_2(t)$. Different kinds of multi-dimensional vibration loci can be excited with this transducer concept; e.g. when both channels are operated at the same bonding frequency an elliptical locus at the tool is achieved. When the two channels are equipped with transducers with different bonding frequencies, multi-frequent complex planar vibration loci can be generated at the tool tip.

The ultrasonic transducer is made of lead zirconate titanate (PZT) for the piezo ceramics and stainless steel for the other parts of the transducers including the coupling

element. The ultrasonic bonding tool is made of hardened stainless steel with a Rockwell hardness of approx. 48 HRC to achieve high reliability of the bonding tool.

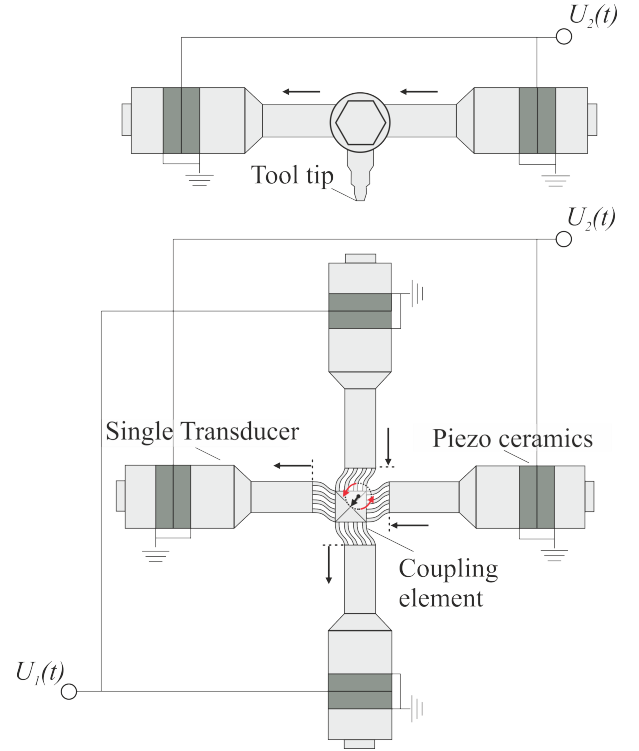


Figure 2: Concept of the multi-dimensional transducer. Four single transducers are mounted to a coupling element in the center and are excited by voltages U_1 and U_2 , so that opposing pairs of transducers move in the same direction.

In **Figure 3** the control concept for an elliptical mono-frequent "circle mode" (top) and a multi-frequent "rectangle mode" (bottom) are shown. In case of the circle mode, the frequency of channel 1 is operated by a Phase Locked Loop controller (PLL-C) which controls the phase difference between voltage and current. Typically, in case of one-dimensional transducers, the PLL controller is set to control the frequency to the resonance frequency (phase 0°) of the transducer; in case of the multi-dimensional transducer and the circle mode, the PLL controller is set to drive both channels in an efficient common operating point which may differ from the resonance frequencies of the channels, depending on the mistuning of the resonance frequencies between both channels. The second controller is an Amplitude Ratio controller (AR-C) to control the ratio between the displacement amplitudes $\hat{x}_1$ and $\hat{x}_2$ of the two channels; the displacement is observed from laser vibrometer measurements directly at the tool tip and by controlling the ratio between the oscillation amplitudes $\hat{x}_1$ and $\hat{x}_2$ to one, a circular locus at the tool tip can be achieved. For this, the phase shift φ of the oscillating voltage $\hat{U}_2 \sin(2\pi f_2 t + \varphi)$ of channel 2 is adjusted.

In case of the rectangle mode, the resonance frequencies of the two channels are significantly different from each

other (e.g. $|f_1 - f_2| \gg 1$ kHz). Both channels are operated in their own resonance frequency by the PLL controller, so both channels are operated with different bonding frequencies f_1 and f_2 . The AR-controller is used to control the ratio between the displacement amplitudes $\hat{x}_1$ and $\hat{x}_2$. The multi-dimensional transducer was operated in both modes - the mono-frequent circle mode and the multi-frequent rectangle mode - under loaded conditions during ultrasonic bonding, **Figure 4**. The figures show the vibration loci, measured by a Polytec CLV 3D laser vibrometer at the tool tip. For the circle mode, the two channels are operated close to the resonance frequency of both channels at approx. 20 kHz. The amplitude ratio for the AR-controller is 1, leading to an elliptical vibration very close to a circular locus. A stable planar vibration locus is achieved by the controllers after a few oscillation cycles. For the rectangle mode, channel 1 was operated at its resonance frequency at approx. 55 kHz and channel 2 at approx. 20 kHz. The amplitude ratio between both channels was set to 0.4. Since there is no fix phase difference between two harmonic signals of different frequencies, the vibration of the multi-frequent vibration locus fills a rectangle of the width of $\hat{x}_1$ and the length of $\hat{x}_2$ during the bond formation.

4. Numerical investigations on the impact of vibration trajectories

Frictional processes in the interface between workpiece and substrate play an important role for the bond formation in the cleaning and deformation phases. Increasing the frictional power in the interface efficiently without increasing the mechanical stress significantly is the main goal to prevent damage of the substrate. In the following, a generalized point contact model for one- and two-dimensional excitation trajectories for numerical investigations on the impact of the vibration loci on the frictional power is presented, which has been published in [42], and [43], **Figure 5**.

The local vectors in the coordinate system P to the projection point W' of the excitation point W, to the contact point S on the substrate, and to the friction force are given by

$$\begin{aligned} \vec{l}_{W'}(t) &= \begin{bmatrix} x_{W'}(t) \\ y_{W'}(t) \end{bmatrix}_P ; \vec{l}_S(t) = \begin{bmatrix} x_S(t) \\ y_S(t) \end{bmatrix}_P \\ \vec{F}_f(t) &= \begin{bmatrix} x_f(t) \\ y_f(t) \end{bmatrix}_P. \end{aligned} \quad (1)$$

The differential equation system during sliding of the contact point vector $\vec{l}_S(t)$ and the friction force vector

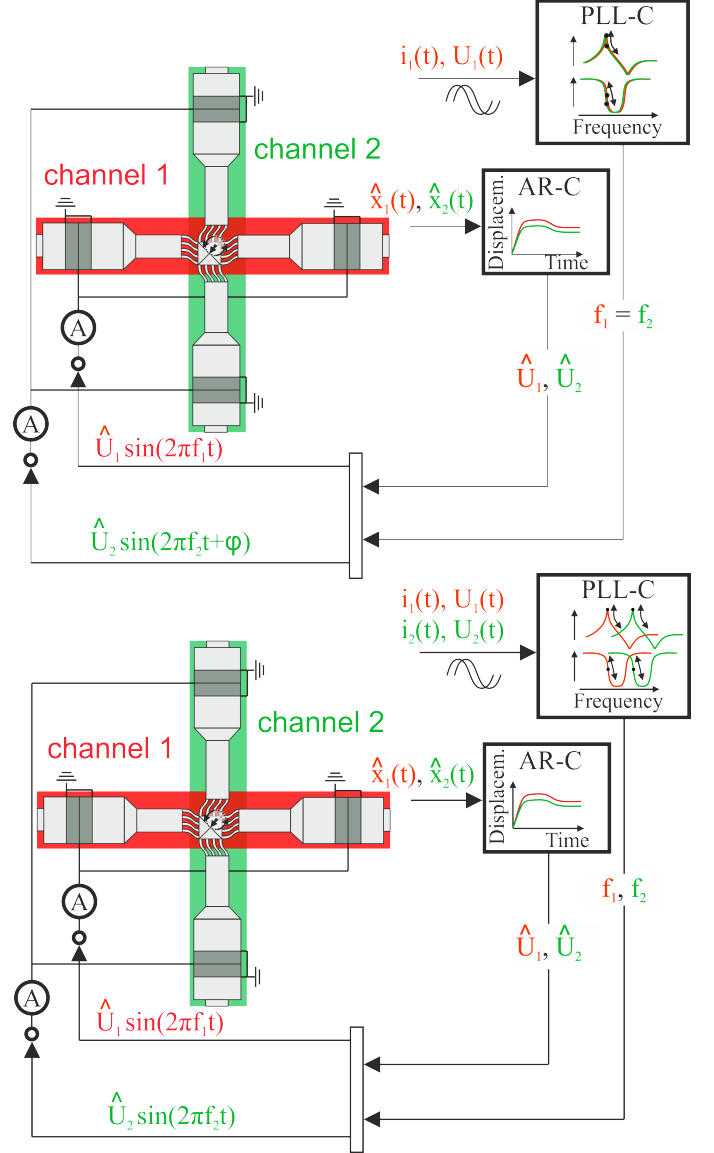


Figure 3: Control system for the multi-dimensional transducer for the circle mode on top and the rectangle mode at the bottom; a PLL-controller is used to control the phase between current and voltage. In case of the circle mode, only the phase of channel 1 is controlled and the frequency f_1 is applied to channel 2. For the rectangle mode, both channels are operated independent from each other. The AR-controller controls the ratio between the displacement amplitudes of both channels. Only for the circle mode, the phase φ of the oscillating voltage $\hat{U}_2 \sin(2\pi f_2 + \varphi)$ of channel 2 is adjusted.

$\vec{F}_f(t)$ is given by

$$\begin{aligned} \dot{\vec{l}}_S &= \frac{\vec{F}_f^T \dot{\vec{l}}_{W'} - \frac{\mu^2}{c_t} F_n \dot{F}_n}{\vec{F}_f^T \vec{F}_f} \vec{F}_f \\ \dot{\vec{F}}_f &= c_t \left(\dot{\vec{l}}_{W'} - \frac{\vec{F}_f^T \dot{\vec{l}}_{W'} - \frac{\mu^2}{c_t} F_n \dot{F}_n}{\vec{F}_f^T \vec{F}_f} \right) \vec{F}_f. \end{aligned} \quad (2)$$

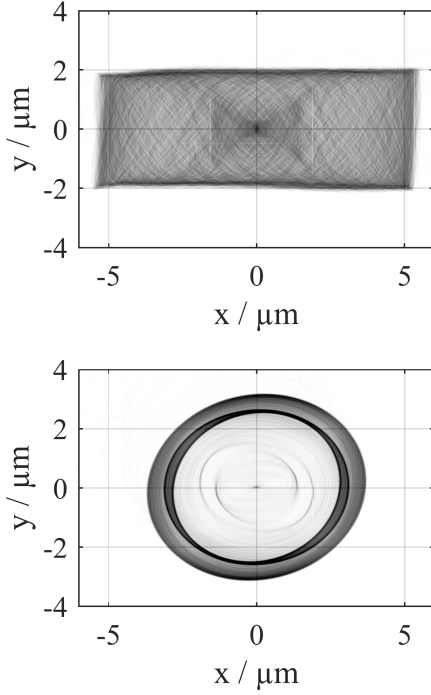


Figure 4: Measurement of the vibration locus at the tool tip by a 3D laser vibrometer during ultrasonic bonding with the rectangle mode at approx. 20 kHz and approx. 55 kHz (top) and the circle mode (bottom) at approx. 20 kHz over a bond duration of 200 ms; the lines are plotted with transparency for the whole bond duration. A amplitude ratio of 0.4 was used for the rectangle mode and of 1 for the circle mode.

During the sticking state, the differential equations of the contact point and the friction force are given by

$$\begin{aligned}\dot{\vec{l}}_S &= \vec{0} \\ \dot{\vec{F}}_f &= c_t \dot{\vec{l}}_{W'}.\end{aligned}\quad (3)$$

The transition from slip to stick state occurs, when the condition $\dot{\vec{l}}_S = \vec{0}$ is satisfied. From **Equation 2** follows the transition criterion

$$\vec{F}_f \dot{\vec{l}}_{W'} - \frac{\mu^2}{c_t} F_n \dot{F}_n = 0. \quad (4)$$

For determining the transition from the stick to slip state, the transition function $\Phi(t)$ is used:

$$\Phi = \left\| \vec{F}_f \right\| - \mu F_n. \quad (5)$$

With **Equation 5**, the transition from stick to slip can be calculated by

$$\Phi \geq 0 \text{ and } \dot{\Phi} > 0. \quad (6)$$

The **Equations 2**, and **3** are implemented with the

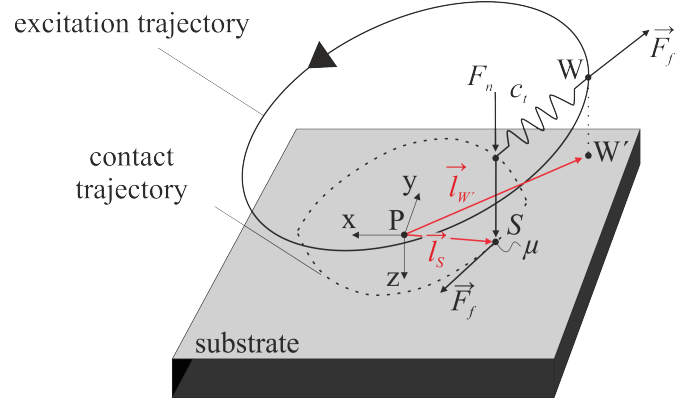


Figure 5: Two dimensional friction point contact model with the excitation point W, the vertical projection point W' of W, the contact stiffness c_t , the normal force F_n , the friction force F_f , the friction coefficient μ , the origin P of the coordinate system, and the contact point S.

transition criterion in **Equations 4** and **6** in MATLAB for simulation of the frictional process at different one- and two-dimensional and multi-frequent excitation loci of the point W. The excitation loci have the form of **Equation 7** where f_1 and f_2 are the bonding frequencies in x- and y-direction in the coordinate system P, $\hat{a}_1$ and $\hat{a}_2$ are the corresponding oscillation amplitudes.

$$\vec{l}_{W'}(t) = \begin{bmatrix} \hat{a}_1 \sin(2\pi f_1 t) \\ \hat{a}_2 \sin(2\pi f_2 t) \end{bmatrix}_P \quad (7)$$

For the simulations, the rectangle mode is investigated; the values of the excitation in x-direction are kept constant with the excitation frequency $f_1 = 20$ kHz and the amplitude $\hat{a}_1 = 6 \mu\text{m}$ and the parameters in y-direction are changed in the range shown in **Table 2**. For the simulation time, 4 ms was chosen which leads to 80 oscillation cycles of the 20 kHz vibration; longer simulation duration showed no difference in the simulation results.

Table 2: Values of the simulation parameters which are varied in a parameter sweep.

Parameter	Description	Values
$\hat{a}_1$	amplitude x-direction	$6 \mu\text{m}$
$\hat{a}_2$	amplitude y-direction	$1, 1.25, \dots, 6 \mu\text{m}$
f_1	frequency x-direction	20 kHz
f_2	frequency y-direction	21, 22, $\dots$ 100 kHz
t	simulation time	4 ms

There are some special cases of planar vibration loci which vary for $f_1 = 20$ kHz and different frequencies f_2 , e.g. $f_2 = 40$ kHz, 45 kHz, and 60 kHz, see **Figure 6**. The period length of a two-dimensional vibration locus can be calculated by the greatest common divisor (gcd) of the two

frequencies:

$$\begin{aligned}
 \gcd(20 \text{ kHz}, 40 \text{ kHz}) &= 20 \text{ kHz} \\
 \gcd(20 \text{ kHz}, 43 \text{ kHz}) &= 1 \text{ kHz} \\
 \gcd(20 \text{ kHz}, 45 \text{ kHz}) &= 5 \text{ kHz} \\
 \gcd(20 \text{ kHz}, 60 \text{ kHz}) &= 20 \text{ kHz}
 \end{aligned} \tag{8}$$

For excitation frequencies $f_2 = 40 \text{ kHz}$ and 60 kHz , the superposition of both harmonic signals leads to a periodic vibration locus, with the period length of the 20 kHz vibration. In case of $f_2 = 2f_1, 4f_2, \dots$ a circular motion and in case of $f_2 = 3f_1, 5f_1 \text{ kHz}, \dots$ a motion following a line can be seen.

For $f_2 = 43 \text{ kHz}$ the period length of an 1 kHz vibration and for $f_2 = 45 \text{ kHz}$ of an 5 kHz vibration can be calculated. For the longer period length in case of $f_2 = 43 \text{ kHz}$ the shape of a rectangle is filled with a higher density compared to $f_2 = 45 \text{ kHz}$; for $f_2 = 45 \text{ kHz}$ the period length of the two-dimensional vibration is shorter, thus the density of the filled rectangle shape is less.

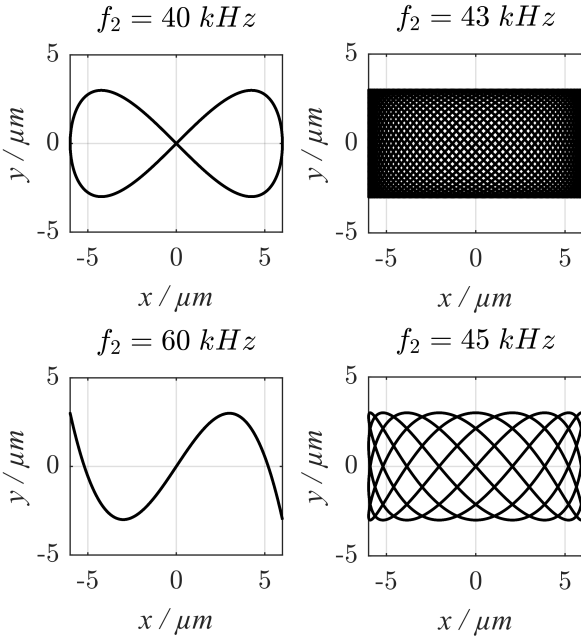


Figure 6: Planar vibration locus with a constant excitation frequency $f_1 = 20 \text{ kHz}$ and different excitation frequencies f_2 . For $f_2 = 40 \text{ kHz}, 45 \text{ kHz}$ and 60 kHz , a stationary vibration locus is observed. For $f_2 = 43 \text{ kHz}$ a non-stationary vibration locus fills the shape of a rectangle in the vibration plane over the vibration duration.

The evaluated simulation results of the parameter sweep are the friction work and the maximum deflection of the contact point S. The maximum deflection can be calculated by the absolute value $\|\vec{l}_{W'}(t)\|$ of the vector from the origin P to the projection point W', **Figure 5**; for a one-dimensional vibration, the maximum deflection is equal to the vibration amplitude. The maximum deflection of

the vibration locus is evaluated as an indicator of the mechanical stress during ultrasonic bonding; increasing the maximum deflection leads typically to higher mechanical stress for already bonded areas and therefore the risk to damage the substrate and already bonded micro junctions is increased.

The results of the parameter sweep are shown in **Figure 7**; on top the ratio W_{2d}/W_{1d} between the frictional work of the multi-dimensional vibration loci and the corresponding one-dimensional vibration with the same maximum deflection as the multi-dimensional vibration is shown. The ratio is proportional to the increase of the frictional power in the interface with the multi-dimensional vibration trajectory without increasing the maximum deflection compared to the corresponding one-dimensional vibration. At the bottom, the maximum deflection of the multi-dimensional vibration loci is shown. The results are plotted over the vibration amplitude $\hat{a}_2$ and the excitation frequency f_2 which are both varied in the range shown in **Table 2**.

By an additional vibration in y-direction with a higher frequency f_2 compared to $f_1 = 20 \text{ kHz}$, the friction work can be increased by a factor of approx. 3.5. The maximum deflection for $\hat{a}_2 = 6 \mu\text{m}$ is about $8.5 \mu\text{m}$ leading to an increase of the maximum deflection compared to the one-dimensional vibration with $\hat{a}_1 = 6 \mu\text{m}$ of a factor about 1.4.

In general, increasing the excitation frequency f_2 for a specific excitation amplitude $\hat{a}_2$ leads to an increased frictional work in the interface; with higher excitation frequencies more oscillation cycles per time unit occur, the friction power is increased and with the constant simulation time of 4 ms , the friction work is increased.

Increasing the excitation amplitude $\hat{a}_2$ for a specific frequency leads to an increased friction work too, but also increasing the maximum deflection which leads to higher oscillating shear forces in the substrate.

Especially for $f_2 = 40 \text{ kHz}$, significantly less deflection compared to the other multi-dimensional vibration loci is reached; the reason can be seen in the form of the vibration locus shown in **Figure 6**. Since the maximum amplitudes $\hat{a}_1$ and $\hat{a}_2$ never occur at the same time and because of the special ratio $f_1/f_2 = 0.5$ the theoretical maximum deflection $\sqrt{\hat{a}_1^2 + \hat{a}_2^2}$ is never reached.

In **Figure 8** the hystereses and the time histories of the friction forces and excitation trajectories in x- and y-direction for $f_2 = 40 \text{ kHz}$ and 60 kHz are shown for the first oscillation cycle of the 20 kHz vibration x_W in x-direction.

For $f_2 = 40 \text{ kHz}$ the contact point S starts sliding, when the absolute value $\|\vec{F}_f(t)\|$ of the contact force reaches the sticking force value μF_N . Because the excitation frequency f_2 in y-direction is twice as high as in x-direction, the zero crossings of the displacement x_W in x-direction occur at the same time as the zero crossing of y_W in y-direction and when the displacement x_W reaches its maximum, y_W crosses zero again. When the displacement

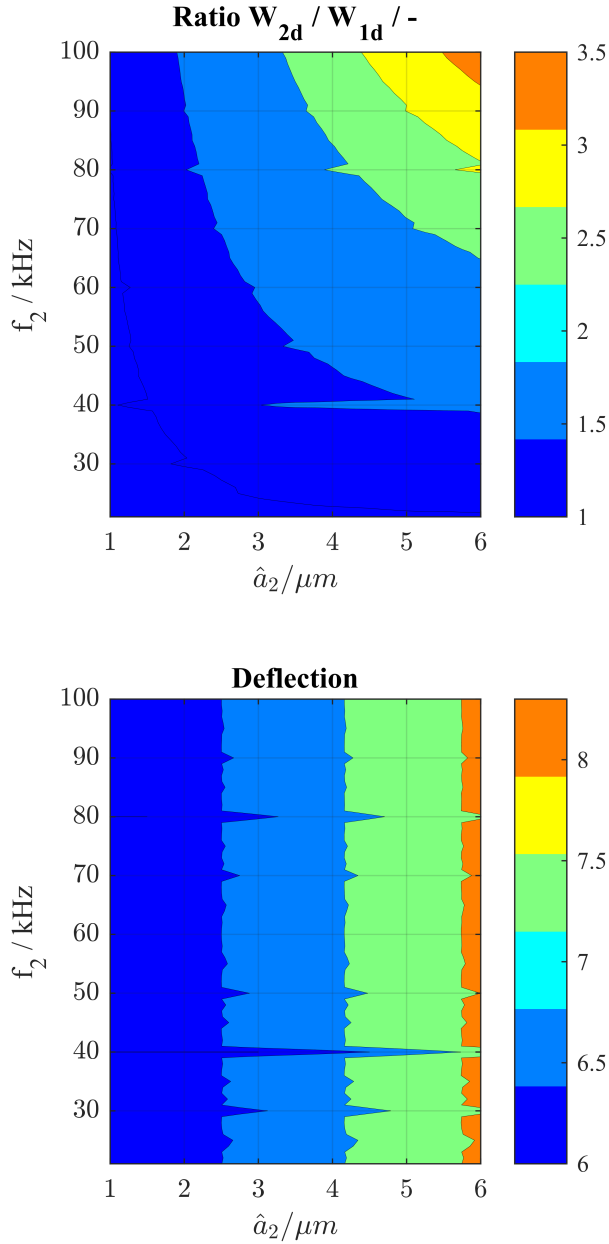


Figure 7: Results of the parameter sweep: ratio W_{2d}/W_{1d} between the frictional work of the multi-dimensional vibration loci and the corresponding one-dimensional vibration with the same maximum deflection (top) and the maximum deflection of the multi-dimensional vibration loci (bottom).

reaches its maximum the velocity becomes zero and the transition criterion from slip to stick **Equation 2** would be fulfilled. In case of $f_2 = 40$ kHz, the displacement y_W in y -direction crosses zero again when x_W reaches its maximum, keeping the contact in the sliding regime. In general, the absolute value of the excitation velocity never reaches zero for $f_2 = 40$ kHz.

In contrast to the permanent sliding of the oscillation with $f_2 = 40$ kHz, sticking occurs with $f_2 = 60$ kHz. Both oscillations reach their maximum displacement amplitude at the same time in opposite direction. At this time, both excitation velocities and thus also the absolute value of the excitation velocity are zero and sticking occurs. After the first quarter of the displacement oscillation x_W , the transition from sliding to sticking occurs the first time. Sliding occurs again with the next zero crossing of the 60 kHz displacement vibration y_W and so on. The sticking phases can also be seen in the hystereses in x - and y -direction; in case of the 60 kHz hysteresis of $F_{f,y}$, the change between sticking and sliding within one period of the 20 kHz vibration can be seen.

The results of the parameter sweep show, that increasing the excitation frequency f_2 is beneficial for increasing the frictional work in the interface without increasing the mechanical stress during ultrasonic excitation. In applications with elastic contact, a minimum amplitude of the one-dimensional vibration is needed to overcome the sticking regime. For ultrasonic transducers, with rising bonding frequency, the attainable displacement amplitude of the ultrasonic transducer decreases, because the allowable velocity amplitude is approximately constant over the frequency; for titanium alloy Ti6Al4V the maximum velocity amplitude is 10 m/s and for other materials, this value is even lower, [44]. Especially for large workpieces like terminals of IGBT modules the minimum amplitudes for overcoming the sticking regime can not be reached for high bonding frequencies. In case of the multi-dimensional vibration, the smaller bonding frequency f_1 can be used to overcome the sticking regime and the second vibration with the higher bonding frequency f_2 can then be used to further increase the input power to the interface without increasing the maximum deflection as much as for the one dimensional case at the lower bonding frequency.

5. Bonding experiments

For bonding experiments the multi-dimensional transducer was operated at the resonance frequencies of approx. $f_1 = 20$ kHz and approx. $f_2 = 55$ kHz of the two channels and the rectangle operation mode was used. For the experiments, a new pin design for IGBT modules is used, **Figure 9**. The connector pins in IGBT modules are used for switching the internal IGBTs and diodes and currently the PressFIT technology for connecting the pins with the substrate is used. A sleeve is connected with the substrate by a solder joint and afterward, the connector pin is pressed into the sleeve, [45]. For handling higher junction temperatures for future generations of the modules, a new pin design for direct ultrasonic bonds between the connector pin and the substrate was developed. At the bottom side of the new pin design a heel was added, where the ultrasonic bonding tool clamps the pin and excites a multi-dimensional vibration.

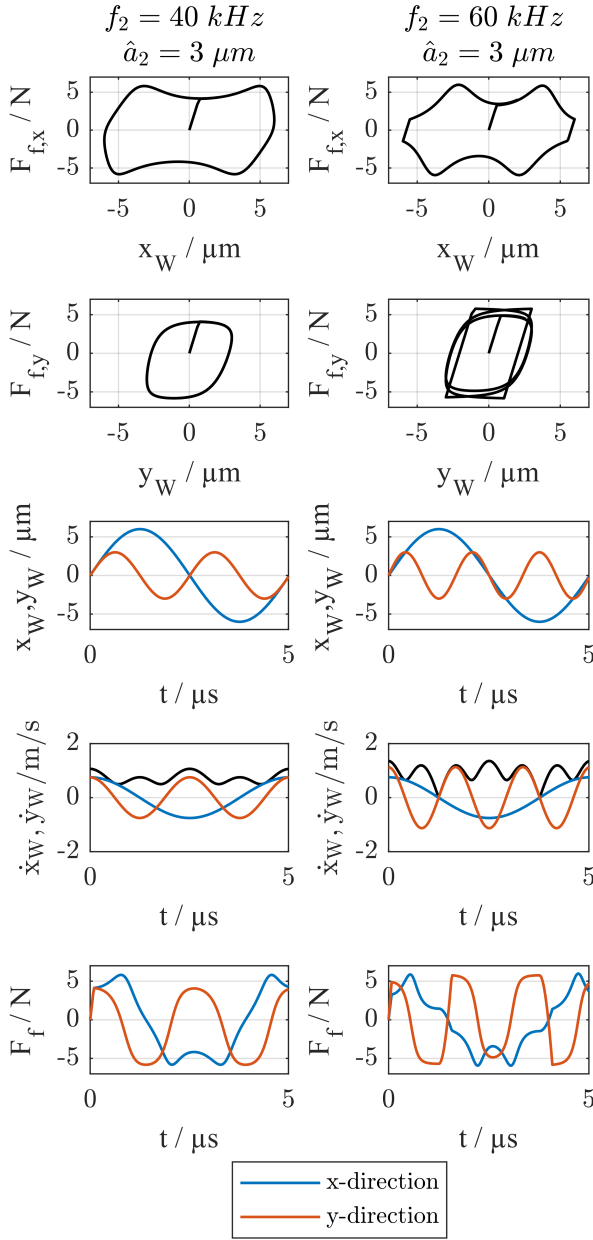


Figure 8: From top to bottom: hystereses of friction forces in x- and y-direction, and time histories of displacement excitations x_W and y_W , the velocity excitations $\dot{x}_W$ and $\dot{y}_W$, and of the friction forces $F_{f,x}$ and $F_{f,y}$. In case of the velocities $\dot{x}_W$ and $\dot{y}_W$, also the absolute value of the two-dimensional excitation velocity is plotted as a black line. The excitation frequencies are $f_1 = 20$ kHz and $f_2 = 40$ kHz / 60 kHz and the excitation amplitudes are $\hat{a}_1 = 6$ μm and $\hat{a}_2 = 3$ μm .

In the bonding experiments, prototypes of the new pin design made of CuSn6 and the ultrasonic bonding tool made of hardened steel with a Rockwell hardness of approx. 48 HRC were used. For the substrate direct bonded copper (DCB) was used. The design of the ultrasonic bonding tool and the pin itself are shown in **Figure 10**.

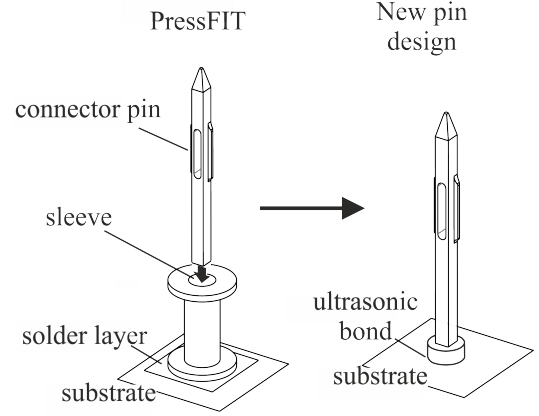


Figure 9: Connector pin design for IGBT-modules. **Left:** PressFIT technology for joining the connector pin with the substrate. **Right:** new pin design for joining the connector pin directly with the substrate by multi-dimensional ultrasonic bonding, [45].

Between the bonding tool and the connector pin, form fit is achieved by the conical geometry of the clamping part of the bonding tool and the connector pin. Design parameters of the bonding tool and the connector pin are the flank angle α , the convexity radius R_c and the radius R_h at the bottom side of the connector pin. In the experiments, the design parameters $\alpha = 37.5^\circ$, $R_c = 3$ mm and $R_h = 1$ mm were used.

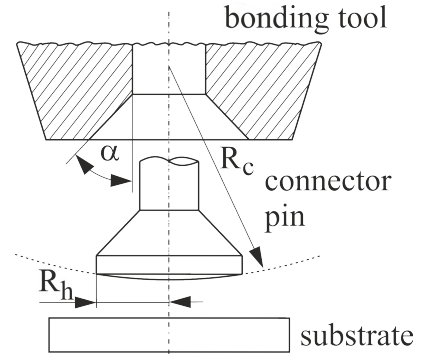


Figure 10: Design of the bonding tool and the connector pin with an form fit clamping mechanism between the tool and pin, [41].

For determination of the bond quality, shear force values F_s of the ultrasonically bonded pins were measured with a DAGE 4000Plus shear tester. The shear force values are determined by destructive testing by applying the shear force F_s to the connector pin parallel to the substrate in a specific height ($h_s = 25$ μm), **Figure 11**. The bond connection is destroyed by the horizontal movement of the shear tool and the maximum shear force value during destructive testing is a measure for the bond quality, [46].

In the experiments, the oscillation amplitude of channel 1 with approx. 20 kHz was kept constant at 6.8 μm and

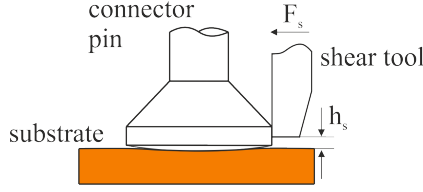


Figure 11: Experimental setup of the shear test: the shear tool moves parallel to the substrate in direction of the connector pin in the shear height h_s . The maximum shear force value F_s during destructive testing is a measure for the bond quality.

the amplitude of channel 2 with approx. 55 kHz was increased up to 3 μm . For comparison between one- and two-dimensional bonding, the same multi-dimensional transducer was used, for one-dimensional bonding experiments at approx. 20 kHz; for this, the amplitude of channel 2 was set to zero and the amplitude of channel 1 was increased beginning from approx. 6.8 μm .

Both experiments were carried out with the same bond normal force (60 N) and bond duration (400 ms). The vibration amplitude was measured with a 3D laser vibrometer at the tool tip for all bonds and the mean value over the bond duration is evaluated. The results of the bonding experiments are shown in **Figure 12**. With rising amplitude $\hat{a}_2$ for the multi-dimensional bonding experiments, the shear values increase from approx. 120 N for $\hat{a}_2 = 0 \mu\text{m}$ to approx. 160 N for $\hat{a}_2 = 3 \mu\text{m}$.

In case of the one-dimensional bonding experiments, the shear force values also increase to approx. 160 N at an oscillation amplitude $\hat{a}_1 = 7.6 \mu\text{m}$. Further increasing the input power leads to an abrupt drop of the shear force values and increases the vibration amplitude of the tool significantly. The reason was found in the increased input power and higher oscillation amplitude; already bonded areas were destroyed because of high oscillating shear stress. This leads to decreasing shear force values and less damping of the vibrating tool with higher oscillation amplitudes. Also, compared to the one-dimensional ultrasonic bonding process, with the rectangle mode the shear force values are reached at slightly lower maximum deflection, compared to the one-dimensional process for a maximum deflection $< 8 \mu\text{m}$.

During the bond formation, highspeed camera videos with 20000 fps were recorded; it was found that no rotation of the connector pin occurred as has been reported in [41]. The reason can be seen in the missing circular ultrasonic excitation of the connector pin; the excitation with constantly changing orientation leads to a stable position of the rotationally symmetric pin and thus to a more robust bond process.

6. Summary and Outlook

In this contribution, the concept of an versatile multi-dimensional transducer and the control concept for two-

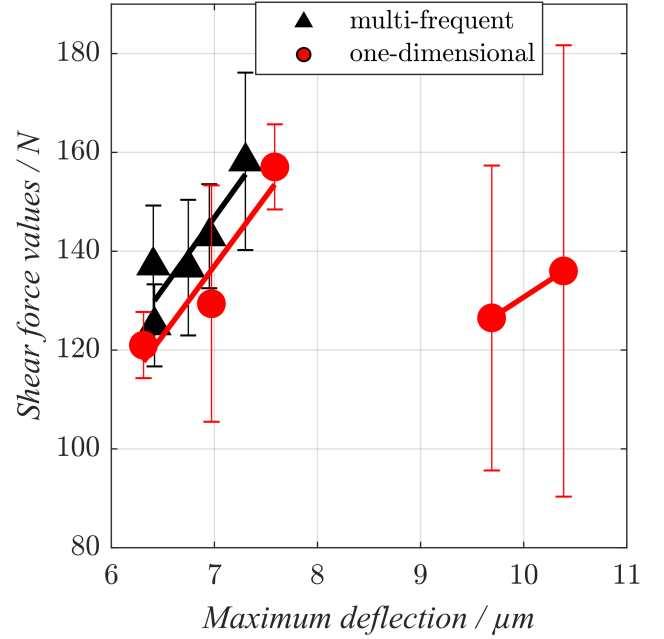


Figure 12: Shear force values of multi-dimensional bonding experiments with the rectangle mode at the frequencies $f_1 \approx 20 \text{ kHz}$ and $f_2 \approx 55 \text{ kHz}$ and one-dimensional bonding experiments at $f_1 \approx 20 \text{ kHz}$. The maximum deflection is calculated from 3D laser vibrometer measurements at the tool tip by $\sqrt{\hat{a}_1^2 + \hat{a}_2^2}$ with the vibration amplitudes $\hat{a}_1$ and $\hat{a}_2$ in the two excitation directions. Both experiments were carried out with the same bond normal force and bond duration. For each parameter set, the shear force values of 10 bonds were evaluated; in the plot, mean and standard deviation values are shown.

different operation modes is presented. The first operation mode is used for planar circular vibration loci ("circular mode") and with the presented control concept, the variation of the amplitude ratio between the two vibration directions is possible. The second operation mode ("rectangle mode") is used for multi-frequent planar vibration loci. Both operation modes have been validated under loaded conditions during ultrasonic bonding by 3D laser vibrometer measurements at the tool-tip.

In simulations with a two-dimensional friction model, the impact of different multi-frequent vibration loci was investigated. Depending on the ratio between the two excitation frequencies, the frictional power in the interface can be increased significantly. Additionally, the maximum deflection of the multi-dimensional vibration is less compared to a one-dimensional vibration with the same frictional power, meaning that the oscillating mechanical shear stress in the substrate is less for a multi-dimensional vibration.

In ultrasonic bonding experiments with a new connector pin design for IGBT-modules, the multi-frequent rectangle mode with the two bonding frequencies $f_1 \approx 20 \text{ kHz}$ and $f_2 \approx 55 \text{ kHz}$ was compared to a one-dimensional ultrasonic

bonding process with the bonding frequency $f_1 \approx 20$ kHz. It was found, that the same shear force values with the rectangle mode could be reached compared to the one-dimensional bond process, but with slightly lower maximum deflection. In case of the one-dimensional bonding experiments and the tested range for the vibration amplitudes, the shear force values dropped when the vibration amplitude was increased beyond $8 \mu\text{m}$. These results indicate, that for the multi-dimensional ultrasonic bonding a wider process window in terms of higher ultrasonic power can be achieved compared to one-dimensional bonding.

The findings of this contribution provide a profound understanding of the principles of multi-dimensional and multi-frequent ultrasonic bonding for future investigations. These should include

- analysis of cross-section images of the interface for one- and two-dimensional bonding. This provides further information on the effect of multi-dimensional bonding on the mechanical stress to the interface by evaluating the changes of the micro-structure of the metals, the deformation of the substrate and failure modes like cracks in the substrate material.
- further experiments with a larger process parameter window to evaluate if multi-dimensional bonding with higher ultrasonic power compared to one-dimensional bonding is possible to further increase the shear force values without damaging the substrate.

Acknowledgement

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

References

- [1] A. Weston, Wire bonding as a technique for semiconductor device assembly, *Microelectronics International* 2 (3) (1985) 26–35. doi:10.1108/eb044183.
- [2] Y. Long, J. Twiefel, J. Wallaschek, A review on the mechanisms of ultrasonic wedge-wedge bonding, *Journal of Materials Processing Technology* 245 (2017) 241 – 258.
- [3] R. Schemmel, T. Hensel, W. Sextro, Numerical and experimental investigations in ultrasonic heavy wire bonding, 6th European Conference on Computational Mechanics (ECCM 6), 2018.
- [4] A. Unger, W. Sextro, S. Althoff, P. Eichwald, T. Meyer, F. Eacock, M. Brökelmann, M. Hunstig, D. Bolowski, K. Guth, Experimental and numerical simulation study of pre-deformed heavy copper wire wedge bonds, in: *Proceedings of the 47th International Symposium on Microelectronics (IMAPS)*, San Diego, CA, US, 2014, pp. 289–294.
- [5] Y. Long, F. Dencker, A. Isaak, J. Hermsdorf, M. Wurz, J. Twiefel, Self-cleaning mechanisms in ultrasonic bonding of al wire, *Journal of Materials Processing Technology* 258 (2018) 58 – 66.
- [6] Y. Long, F. Dencker, A. Isaak, C. Li, F. Schneider, J. Hermsdorf, M. Wurz, J. Twiefel, J. Wallaschek, Revealing of ultrasonic wire bonding mechanisms via metal-glass bonding, *Materials Science and Engineering: B* doi:https://doi.org/10.1016/j.mseb.2018.11.010.
- [7] Y. Daud, M. Lucas, Z. Huang, Modelling the effects of superimposed ultrasonic vibrations on tension and compression tests of aluminium, *Journal of Materials Processing Technology* 186 (1) (2007) 179 – 190. doi:https://doi.org/10.1016/j.jmatprotec.2006.12.032.
- [8] K. B. Pedersen, D. Benning, P. K. Kristensen, V. N. Popok, K. Pedersen, Interface structure and strength of ultrasonically wedge bonded heavy aluminium wires in si-based power modules, *Journal of Materials Science: Materials in Electronics* 25 (7) (2014) 2863–2871. doi:10.1007/s10854-014-1953-8.
- [9] D. Tabor, Junction growth in metallic friction: the role of combined stresses and surface contamination, *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 251 (1266) (1959) 378–393. doi:10.1098/rspa.1959.0114.
- [10] M. Sbeiti, Thermomechanische beschreibung der ausbildung einer intermetallischen phase beim ultraschall-wedge/wedge-drahtbonden im rahmen der theorie der materiellen kräfte, Ph.D. thesis (2013).
- [11] Y. Ding, J.-K. Kim, Numerical analysis of ultrasonic wire bonding: Part 2. effects of bonding parameters on temperature rise, *Microelectronics Reliability* 48 (1) (2008) 149 – 157. doi:https://doi.org/10.1016/j.microrel.2007.01.083.
- [12] Y. Y. Zhao, D. Li, Y. S. Zhang, Effect of welding energy on interface zone of alcu ultrasonic welded joint, *Science and Technology of Welding and Joining* 18 (4) (2013) 354–360. doi:10.1179/1362171813Y.0000000114.
- [13] A. Das, I. Masters, D. Williams, Process robustness and strength analysis of multi-layered dissimilar joints using ultrasonic metal welding, *The International Journal of Advanced Manufacturing Technology* doi:10.1007/s00170-018-2936-3.
- [14] P. Chauhan, Z. W. Zhong, M. Pecht, Copper wire bonding concerns and best practices, *Journal of Electronic Materials* 42 (8) (2013) 2415–2434. doi:https://doi.org/10.1007/s11664-013-2576-1.
- [15] D. Kim, R. Willmot, D. Peroulis, A high-efficiency low-cost wire-bond loop antenna for cmos wafers, 2009 IEEE Antennas and Propagation Society International Symposium (2009) 1–4.
- [16] R. Gilardonì, Ribbon bonding for high frequency applications advantages of ribbon and the impact on the microwave market, in: *IMAPS/SEMI Advanced technology workshop on wire bonding*, San Francisco, 2008, pp. 1–5.
- [17] B. Ong, M. Helmy, S. Chuah, C. Luechinger, G. Wong, Heavy al ribbon interconnect: An alternative solution for hybrid power packaging, in: *Proc. 37th Int. Symposium on Microelectronics, IMAPS*, 2004.
- [18] N. Marenco, M. Kontek, W. Reinert, J. Lingner, M. Poech, Copper ribbon bonding for power electronics applications, in: 2013 European Microelectronics Packaging Conference (EMPC), 2013, pp. 1–4.
- [19] S. Mostafavi, D. F. Hesser, B. Markert, Effect of process parameters on the interface temperature in ultrasonic aluminum wire bonding, *Journal of Manufacturing Processes* 36 (2018) 104 – 114. doi:https://doi.org/10.1016/j.jmapro.2018.09.020.
- [20] Y. Nishimura, K. Kido, F. Momose, T. Goto, Development of ultrasonic welding for igbt module structure, in: 2010 22nd International Symposium on Power Semiconductor Devices IC's (ISPSD), 2010, pp. 293–296.
- [21] S. Nambu, K. Seto, J.-Y. Lin, T. Koseki, Development of a bonding interface between steel/steel and steel/ni by ultrasonic welding, *Science and Technology of Welding and Joining* 23 (8) (2018) 687–692. doi:10.1080/13621718.2018.1473077.
- [22] B. Sanga, R. Wattal, D. S. Nagesh, Mechanism of joint formation and characteristics of interface in ultrasonic welding: Literature review, *Periodicals of Engineering and Natural Sciences (PEN)* 6 (2018) 107. doi:10.21533/pen.v6i1.158.
- [23] R. John, O. Vermesan, R. Bayerer, High temperature power electronics igbt modules for electrical and hybrid vehicles, *IMAPS, High Temperature Electronics Network (HiTEN)* 1 (2009) 199–204.
- [24] A. Karch, Neue lötlegierung für erweiterte einsatztemperaturen,

- 2018.
- [25] V. Müller, H. Lewitschnig, N. Kortik, W. Kanert, Quality assurance in automotive electronics, *Elektrotechnik und Informationstechnik* 128 (2011) 371–374. doi:10.1007/s00502-011-0048-y.
- [26] L. Levine, The ultrasonic wedge bonding mechanism: Two theories converge, in: *ISHM*, Vol. 95, 1995, pp. 242–246.
- [27] J. Onuki, M. Koizumi, I. Ishikawa, Effects of frequency and surface cleanliness of al–si electrode on ultrasonic bonding characteristics of thick al wire bonding, *Materials Transactions, JIM* 37 (9) (1996) 1492–1496. doi:10.2320/matertrans1989.37.1492.
- [28] Y. H. Chan, J.-K. Kim, D. Liu, P. C. K. Liu, Y. M. Cheung, M. W. Ng, Effects of bonding frequency on au wedge wire bondability, *Journal of Materials Science: Materials in Electronics* 19 (3) (2008) 281–288. doi:10.1007/s10854-007-9312-7.
- [29] H. K. Charles, K. J. Mach, S. J. Lehtonen, A. S. Francomacaro, J. S. DeBoy, R. L. Edwards, High-frequency wirebonding: process and reliability implications, in: *52nd Electronic Components and Technology Conference 2002*. (Cat. No.02CH37345), 2002, pp. 881–890. doi:10.1109/ECTC.2002.1008204.
- [30] H. Charles, K. Mach, S. Lehtonen, A. Francomacaro, J. DeBoy, R. Edwards, Wirebonding at higher ultrasonic frequencies: reliability and process implications, *Microelectronics Reliability* 43 (1) (2003) 141 – 153. doi:https://doi.org/10.1016/S0026-2714(02)00118-X.
- [31] G. Heinen, R. J. Stierman, D. Edwards, L. Nye, Wire bonds over active circuits, in: *1994 Proceedings. 44th Electronic Components and Technology Conference*, 1994, pp. 922–928. doi:10.1109/ECTC.1994.367518.
- [32] R. Schemmel, S. Althoff, W. Sextro, A. Unger, M. Hunstig, M. Brökelmann, Effects of different working frequencies on the joint formation in copper wire bonding, in: *CIPS 2018; 10th International Conference on Integrated Power Electronics Systems*, 2018, pp. 1–6.
URL <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8403137&isnumber=8402818>
- [33] J. Tsujino, T. Tamura, T. Uchida, T. Ueoka, Characteristics of two-vibration-system ultrasonic plastic welding with 90 khz and 20 khz vibration systems at right angles, *Japanese Journal of Applied Physics* 35 (11R) (1996) 5884.
- [34] T. Asami, Y. Higuchi, H. Miura, Ultrasonic metal welding by longitudinal-torsional vibration source consisting of two transducers, *The Journal of the Acoustical Society of America* 140 (4) (2016) 3423–3423. doi:10.1121/1.4971013.
- [35] E. Hetrick, J. Baer, W. Zhu, L. Reatherford, A. Grima, D. Scholl, D. Wilkosz, S. Fatima, S. Ward, Ultrasonic metal welding process robustness in aluminum automotive body construction applications, *Weld. J* 88 (7) (2009) 149–158.
- [36] T. Asami, H. Miura, Ultrasonic welding of dissimilar metals by vibration with planar locus, *Acoustical Science and Technology* 36 (3) (2015) 232–239. doi:10.1250/ast.36.232.
- [37] T. Asami, H. Miura, Longitudinaltorsional vibration source consisting of two transducers with different vibration modes, *Japanese Journal of Applied Physics* 55 (7S1) (2016) 07KE08.
- [38] T. Asami, Y. Tamada, Y. Higuchi, H. Miura, Ultrasonic metal welding with a vibration source using longitudinal and torsional vibration transducers, *Japanese Journal of Applied Physics* 56 (7S1) (2017) 07JE02.
- [39] Y. Tamada, T. Asami, H. Miura, Welding characteristics of cu and al plates using planar vibration by a dumbbell-shaped ultrasonic complex vibration source, *Japanese Journal of Applied Physics* 57 (7S1) (2018) 07LE12.
- [40] C. Dymel, R. Schemmel, T. Hemsel, W. Sextro, M. Brökelmann, M. Hunstig, Experimental investigations on the impact of bond process parameters in two-dimensional ultrasonic copper bonding, in: *Proceedings of IEEE CPMT Symposium Japan*, Kyoto, Japan, 2018, 2018, pp. 1–4.
- [41] C. Dymel, P. Eichwald, R. Schemmel, T. Hemsel, M. Brökelmann, M. Hunstig, W. Sextro, Numerical and statistical investigation of weld formation in a novel two-dimensional copper-copper bonding process, in: (Proceedings of 7th Electronics System-Integration Technology Conference, Dresden, Germany), 2018, pp. 1–6.
- [42] B. Yang, C. Menq, Characterization of 3d contact kinematics and prediction of resonant response of structures having 3d frictional constraint, *Journal of Sound and Vibration* 217 (5) (1998) 909 – 925. doi:https://doi.org/10.1006/jsvi.1998.1802.
- [43] L. Panning, Auslegung von Reibelementen zur Schwingungsdämpfung von Turbinenschaufeln, *Fortschritt-Berichte VDI: Reihe 11, Schwingungstechnik*, VDI-Verlag, 2005.
URL <https://books.google.de/books?id=0VHAAgAACAAJ>
- [44] E.-G. Lierke, W. Littmann, T. Hemsel, Zur theorie der piezoelektrischen ultraschallverbundschwinger mit praktischen schlussfolgerungen für den entwicklungsingenieur.
URL <http://digital.ub.uni-paderborn.de/ubpb/urn/urn:nbn:de:hbz:466:2-7370>
- [45] P. Eichwald, S. Althoff, R. Schemmel, W. Sextro, A. Unger, M. Brökelmann, M. Hunstig, Multi-dimensional ultrasonic copper bonding new challenges for tool design, *IMAPSource Vol. 2017*, No. 1. doi:https://doi.org/10.4071/isom-2017-WP43_071.
- [46] German Welding Society (DVS), Technical Bulletin DVS 2811 - Test Procedures for Wire Bonded Joints, Tech. rep., Translation of the german issue (2017).