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Impact of multi-dimensional vibration trajectories on quality and failure modes in ultrasonic bonding

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Abstract

Ultrasonic joining is a common industrial process. To build electrical connections in the electronics industry, uni-axial and torsional ultrasonic vibration have been used to join different types of workpieces for decades. Many influencing factors like ultrasonic power, bond normal force, bond duration and frequency are known to have a high impact on bond quality and reliability. Multi-dimensional bonding has been investigated in the past to increase ultrasonic power and consequently bond strength. This contribution is focused on the comparison of circular, multi-frequency planar and uniaxial vibration trajectories used for ultrasonic bonding of copper pins on copper substrate. Bond quality was analyzed by shear tests, scanning acoustic microscopy and interface cross-sections.

Key words

Ultrasonic bonding, ultrasonic welding, multi-dimensional bonding, multi-frequency vibration.

I. Introduction

For decades uni-axial and torsional ultrasonic bonding and welding have been used to create electrical interconnections in electrical devices like battery tabs or the outer connections of modules incorporating power semiconductors. Therein different types of work pieces with varying effective contact areas like wires (<0.5 mm^2), ribbons (0.2-2.5 mm^2), and control/power terminals (4-16 mm^2) are connected to different substrates. With rising contact area, the ultrasonic power required for the bonding process rises. Increased ultrasonic power is realized by increasing ultrasonic vibration amplitude, normal force, or both. This increases the resulting mechanical stress in the substrate during the bonding process and may finally lead to failure modes like cratering and delamination of the substrate structure, **[1]**.

Several different researchers have investigated multi-dimensional ultrasonic bonding as an alternative welding system. Asami et al. **[2], [3]** presented two multi-dimensional transducer concepts for elliptical and multi-frequency ultrasonic vibration trajectories in ultrasonic bonding. Bonding tests showed that multi-dimensional bonding can increase the bond strength. Tsujino **[4]** investigated a two-dimensional ultrasonic transducer in ultrasonic welding of dissimilar metal foils. The required vibration velocity and clamping force for welding the metal foils could be decreased significantly compared to a conventional linear vibration system.

Thus, the reliability of bond connections might be enhanced in two ways by multi-dimensional vibration in ultrasonic bonding: higher bond strength yields more robust interconnections, or reduced ultrasonic power leads to same bond strength but lower stresses during bonding. Whether such failures can be avoided depends on the normal force and the amplitudes and frequencies of the multi-dimensional vibration trajectory.

This contribution aims to determine the benefits and disadvantages of circular and multi-frequency planar against standard uniaxial ultrasonic excitation regarding the intended decrease of mechanical stress in the substrate. To this end, the effect of different multi-dimensional vibration trajectories on bond quality and failure modes of connector pins bonded on substrate is described based on experimental results. The bond strength is determined by shear tests and the failure modes are analyzed by scanning acoustic microscopy (SAM) and scanning electron microscopy (SEM) and optical microscopy of cross-sections of the bonds.

II. Experimental methods

A. *Equipment*

A multi-dimensional transducer was set up to perform the bonding experiments; the transducer concept was already presented by Schemmel et al. in **[5]**. Four single transducers are mounted to a coupling element in the center and the pairs of transducers opposing each other are acting in the same direction, **Fig. 1**. The two pairs of opposing transducers are called “channels” and are operated by the excitation voltages U_1 and U_2.

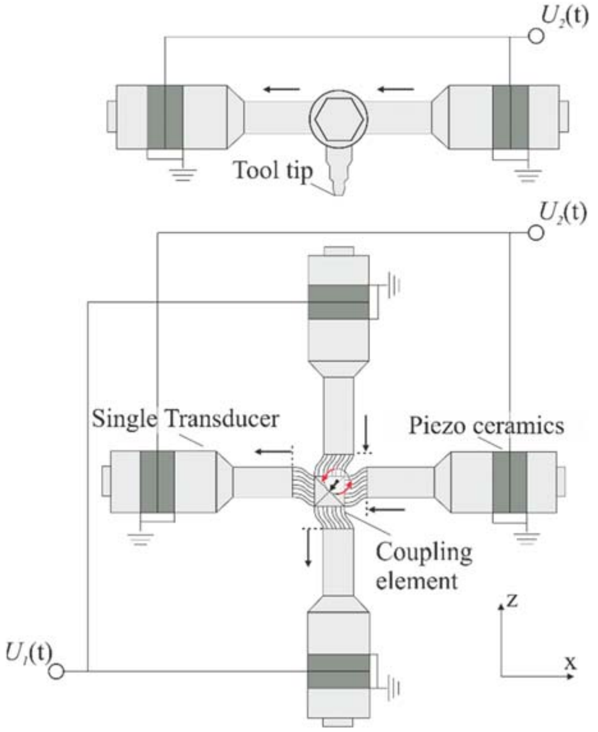

Fig. 1: Concept of the multi-dimensional transducer: four single transducers are mounted to a coupling element in the center and are excited by voltages U_1 and U_2, so that opposing pairs of transducers act in the same direction, [5].

Different kinds of multi-dimensional vibration trajectories can be excited by this transducer concept:

- Elliptical vibration mode (E-VM):
  Both channels are operated at the same excitation frequency; an elliptical vibration locus at the tool tip is achieved. The ratio of the vibration amplitudes in x- and z-direction can be controlled (ratio 1 describes a circular locus).
- Multi-frequency vibration mode (MF-VM):
  The two channels are equipped with transducers with different resonance frequencies; a multi-frequency vibration locus at the tool tip is achieved. The working frequency of both channels is controlled independently from each other by a phase locked loop (PLL) controller.
- One-dimensional vibration mode (1d-VM):
  Only one channel is excited; at the tool tip a one-dimensional vibration in the direction of the excited channel is achieved.

The transducer is mounted in a versatile test rig presented by Dymel et al. in **[6]**. A prototype connector pin was designed, which can be bonded directly to the substrate, **Fig. 2**.

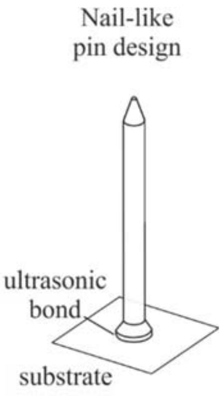

Fig. 2 Prototype connector pin design for direct bonding on substrate.

The ultrasonic vibration is transmitted from the bonding tool to the bottom side of the new pin by a conical clamping mechanism shown in **Fig. 3**. 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 pin; the design of the multi-dimensional bonding tool is described in **[5] - [7]**.

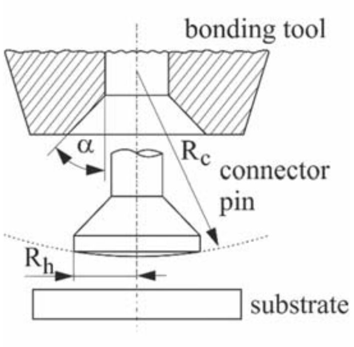

Fig. 3 Design parameters of bonding tool and connector pin: flank angle *α*, convexity R_C, and bottom radius R_h, [5] - [7].

A laser vibrometer (Polytec CLV 3D) captured the complex vibration locus at the tool tip during ultrasonic bonding and a high speed camera (Photron FASTCAM APX RS) was used for further analysis of the dynamics of the connector pin. The shear strengths of the ultrasonically bonded pins were measured with a shear tester (DAGE 4000Plus, shear height 35 µm). Scanning acoustic microscope images (SAM 300 PVA TePla, measuring head 100 MHz) were analyzed in order to determine possible failure modes in the interface between connector pin and substrate.

B. Experimental procedure

The bonding experiments were performed at 20 kHz (E-VM and 1d-VM) and combined 20 kHz (x-axis) and 55 kHz (z-axis) (MF-VM). The bond normal force F_{bn} was kept constant over the whole bond duration t_b. To compare the three different operation modes, bond parameters were chosen such that the resulting mean shear forces of the different vibration modes lay in the same range of approx. 90-100 N.

For the E-VM the bond normal force F_{bn} and the bond duration t_b were increased in comparison to the MF-VM from 60 N to 80 N and from 400 ms to 500 ms, because further increasing the vibration amplitudes lead to decreasing shear strengths. For the 1d-VM, changing the vibration amplitude had a high impact on the resulting shear forces; thus, in the first step, the driving voltage of the channel was adjusted, and afterwards, the bond duration was increased from 400 ms to 450 ms for fine-tuning of the shear strength.

The ultrasonic power was adjusted by the driving voltages U_1 and U_2 for the three different vibration modes. As different transducer types were used, voltages are not the right measure to compare ultrasonic power. Instead, the mean values of the measured vibration amplitudes $\hat{x}$ and $\hat{z}$ at the tool tip are listed together with the bond parameters used in the experiments in **Table 1**. Additionally, the maximum overall amplitude $\hat{s}$ ($\sqrt{\hat{x}^2 + \hat{z}^2}$ for the MF-VM) is given as a measure for direct comparison.

Table 1 Bond normal force F_{bn}, bond duration t_b and vibration amplitudes $\hat{x}$, $\hat{z}$ and $\hat{s}$ at the tool tip.

	F_{bn} / N	t_b / ms	$\hat{x}$ / µm	$\hat{z}$ / µm	$\hat{s}$ / µm
E-VM	80	500	4,7	2,2	4,7
MF-VM	60	400	5,4	1,9	5,4
1d-VM	60	450	5,3	-	5,3

II. Results

The shear forces of ten bonds each were evaluated; mean values and standard deviations are listed in **Table 2**. For the 1d-VM, shear force values were evaluated when testing in direction of the vibration (1d-VM-a) and perpendicular to the direction of the vibration (1d-VM-b). Lower shear force values occured when testing in direction of the vibration; for the E-VM and MF-VM, the shear strengths did not depend on the direction of shear testing.

Table 2 Shear force values.

	E-VM	MF-VM	1d-VM-a	1d-VM-b
Mean	95,45 N	99,16 N	88,32 N	93,58 N
Std. Dev.	13,38 N	11,16 N	8,67 N	7,88 N

Further analysis with high-speed camera videos showed a rotation of the pin in opposite direction to the rotation of the ultrasonic vibration of the tool tip in case of the E-VM. In **Fig. 4** single frames of a video taken in the middle (at approx. 200 ms) and close to the end of the bond process are shown. The changing position of the marker on the connector pin indicates the rotation; one full rotation lasted about 110 ms in these experiments.

The rotation of the pin occurred due to the elliptical motion of the bonding tool and its rolling contact with the pin: tangential forces and their resulting torque rotate the pin, if the torque is high enough to overcome the friction between the connector pin and the substrate.

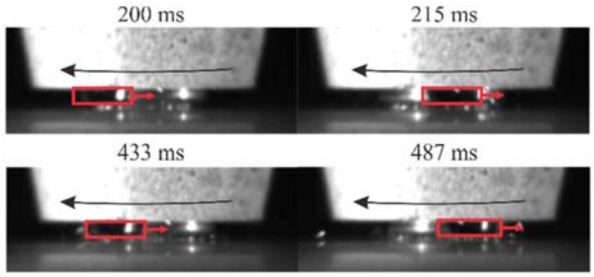

Fig. 4 Single frames of high-speed camera video at four different times during bonding with the E-VM. The changing position of the marker (red box) on the connector pin indicates rotation of the pin in opposite direction to the rotation of the tool (black arrow).

The rotation mainly depends on the bond normal force, the vibration amplitudes and the amplitude ratio of both directions. By using amplitude ratios not equal to one to increase the difference between the half axes of the ellipse (ratio one describes a circle), decreasing vibration amplitudes in general, or increasing bond normal force the rotation can be reduced. Gross sliding because of the rotation breaking already formed micro-welds and thus a rotation of the pin for the whole bond duration decreases the bond strength and leads to failure modes like micro-cracks, voids and high penetration depth of the pin in the substrate.

In contrast to the E-VM, pin rotation was not observed in the MF-VM and the 1d-VM. In the 1d-VM the exciting elliptical excitation locus is obviously missing. For further detailed discussion of the rotation mechanism, laser-measurements of the vibration at the tool tip during bonding for E-VM and MF-VM are shown in **Fig. 5**. For the E-VM, two laser-measurements are shown, as the degree of rotation was different even though the bonding parameters were the same.

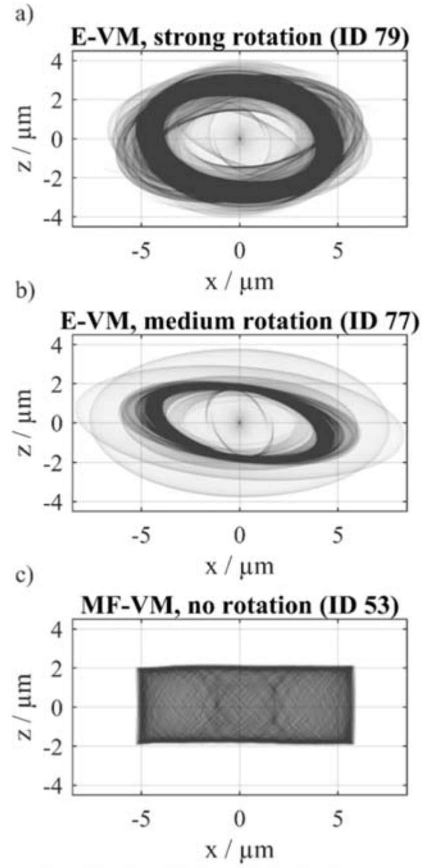

Fig. 5 Laser measurements of the planar vibration locus at the tool tip: a) E-VM, strong rotation of the connector pin until the end of bond duration, b) E-VM, medium rotation that stops during the bond duration, and c) MF-VM, no rotation.

Fig. 5 a) shows the trajectories for a bond process with strong pin-rotation (approx. 5 full rotations during bond duration). The pin rotation stopped and restarted several times during bond formation. Thus, the load for the bonding tool changed due to the changing friction status from sticking to sliding and as a result of this, the vibration amplitude strongly varied (ellipses with different half axes).

Fig. 5 b) shows trajectories for a bond process using the same bonding parameters as the process shown in **Fig. 5 a),** but with less rotation of the pin. The rotation with gross sliding stopped in the early stage of the bond process after less than one full rotation at approx. 100 ms. After the rotation stopped, only very slow and continuous rotation of the pin with micro-sliding of the connector pin was observed. Thus, the resulting nearly constant mechanical load for the bond led to a more constant elliptical vibration locus.

The vibration locus of the MF-VM with 20 kHz excitation along the x-axis and 55 kHz excitation along the z-axis is shown in **Fig. 5 c)**. When using two different working frequencies for the two channels, the period length of the resulting planar vibration is calculated by the greatest common divisor (gcd), **[5]**, and commonly is orders of magnitude larger than the individual period length and often practically infinite as both frequencies vary slightly during the bond process. This means that the vibration locus is not stationary during the bond duration and fills the shape of a rectangle over time. A pin rotation could not be observed, as the tangential force between tool and pin varies quickly in amplitude and direction, cancelling its effect out in time average.

To investigate the effect of the rotation on the quality of the bond interface, scanning acoustic microscope images were taken with their focus on the interface plane for ten bonds of each vibration mode. **Fig. 6** shows the results: bonded areas in the interface appear as black spots, as the ultrasound is not reflected, while bright spots indicate voids or gaps in the interface. In case of the strongly rotated pin (ID 79), the interface area is larger than the one of the less rotated pin (ID 77), but more bright spots appear in the interface, **Fig. 6 a)**. The rotation of the connector pin until the end of bond formation obviously results in broken micro welds. All bonds made by MF-VM showed a homogenously bonded interface without visible voids, **Fig. 6 b)**. For bonds made using both E-VM and MF-VM, the interface area is almost circular. In contrast, the interfaces formed using the 1d-VM are elliptical and orientated in direction of the ultrasonic vibration, **Fig. 6 c)**. Less voids appear compared to the E-VM, but for the MF-VM the interface is more homogenous, which means that this mode is probably the best one for reliable interconnections.

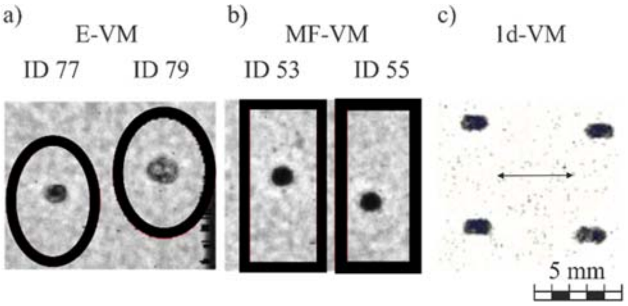

Fig. 6 Scanning acoustic microscope images of the bond interface for a) E-VM, b) MF-VM, and c) 1d-VM (the arrow indicates the direction of vibration).

To further investigate the quality of the interconnections, cross-sections have been grinded, ion beam polished and analyzed by scanning electron microscopy (SEM) and optical microscopy for the three different vibration modes. Images of a bond made with E-VM are shown in **Fig. 7**.

Because of the rotation of the connector pin, several cracks and voids in the interface between connector pin and substrate emerged. The SEM image **Fig. 7 a)** shows an image detail of the interface between connector pin and substrate; a small gap without intermetallic connection and rough surfaces due to frictional processes is visible. The second image detail in **Fig. 7 b)** shows a piece of the substrate with fine grained microstructure, bonded to the connector pin, but debonded from the substrate. In case of this bond a “medium” rotation, compared to the bond with ID 77, was observed. The gross slippage of the connector pin during rotation shears already bonded areas and leads to large deformation of the substrate in the interface, which results in strong grain refinement.

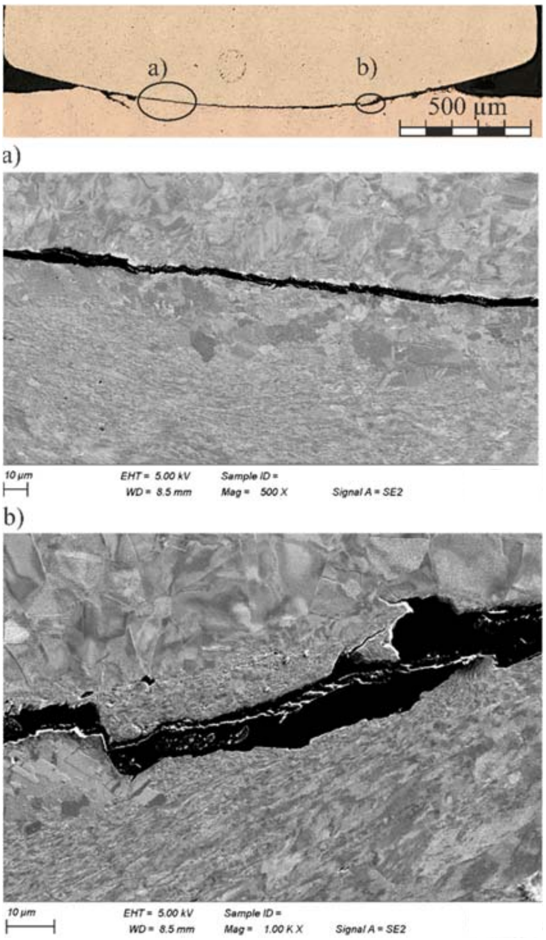

Fig. 7 Optical microscopy image of the cross-section (top) and SEM images of highlighted areas in the interface of the bond made with the E-VM.

Images of a bond made using MF-VM are shown in **Fig. 8**. Intermetallic bonded areas can be seen in the image detail **Fig. 8 a)**; for the MF-VM, no rotation and thus no gross slippage occurs, the bonded areas remain intact. In **Fig. 8 b)**, a larger area of the interface is shown; the interface is homogenously bonded and a homogenously distributed grain texture of the substrate can be seen.

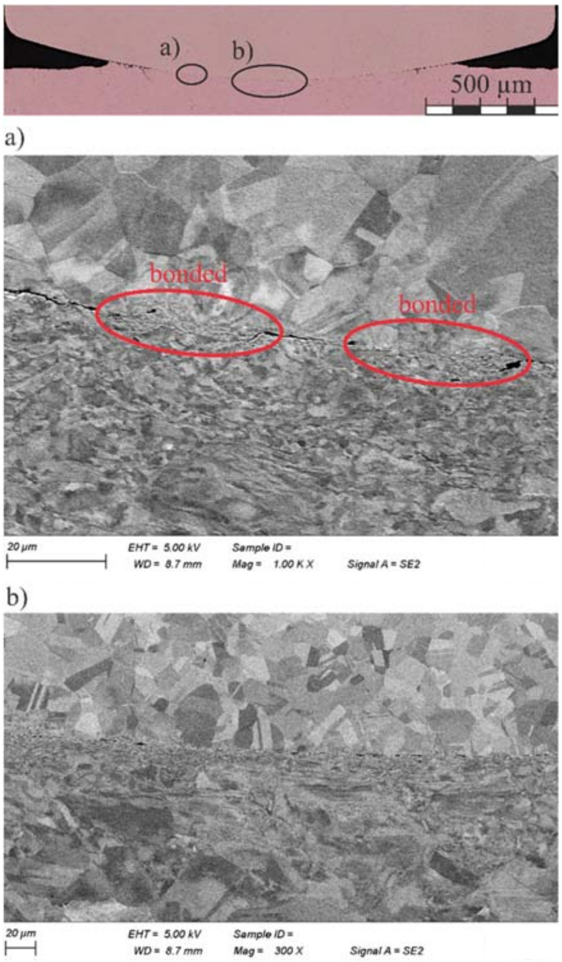

Fig. 8 Optical microscopy image of the cross-section (top) and SEM images of highlighted areas in the interface of the bond made with the MF-VM.

The images of the cross section in direction of the vibration of the bond made with 1d-VM are shown in **Fig. 9.** The interface is homogenously bonded without any destroyed junctions. In the grain refinement area of the substrate, the grain structure shows a direction dependent deformation in direction of the vibration, which does not occur for the E-VM and MF-VM, **Fig. 9 a)**. In the image detail of **Fig. 9 b)**, an intermetallic bonded area as in **Fig. 8 a)** (MF-VM) is visible.

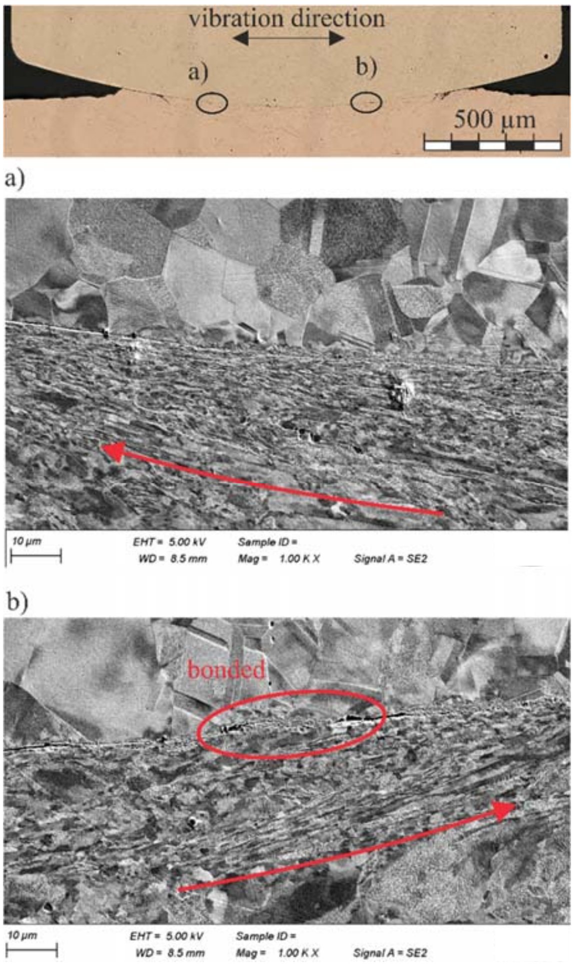

Fig. 9 Optical microscopy image of the cross-section (top) and SEM images of highlighted areas in the interface of the bond made with the 1d-VM in direction of the vibration. In b) the deformation direction of the grains is indicated by the arrow.

Since the connector pin is harder than the substrate, no visible deformation of the connector pin itself and only a small grain refinement area directly at the interface of the intermetallic bond can be seen in all images of the different vibration modes.

III. Conclusion

Multi-dimensional ultrasonic bonding can increase the bond strength. For the investigated rotationally symmetric connector pins, elliptical vibration trajectories can generate rotation with gross slippage of the work piece, which results in damaging newly built interconnections and thus destabilizes the bond process. Using multi-frequent planar vibrations overcomes this issue. Scanning acoustic microscope images show, that when using elliptical or multi-frequency vibration trajectories, a nearly circular interface area is created and no direction dependency appears. In case of the one-dimensional vibration mode, an elliptical interface area is created, stretched in direction of the vibration. Consequently, different shear strengths along and perpendicular to the direction of the vibration was measured only in case of the one-dimensional vibration mode. For the multi-frequent vibration mode, the lowest bond normal force and bond duration was required to reach shear strengths of approx. 90-100 N. For the one-dimensional vibration, the same bond normal force and slightly longer bond duration was needed. In case of the elliptical vibration mode, the highest bond normal force and even higher bond duration was required. For the elliptical vibration mode, cracks/voids and gaps between connector pin and substrate and large deformation of the substrate were found in the scanning acoustic microscope images and images of cross-sections as a result of the rotation of the connector pin.

Less voids/cracks were found for the one-dimensionally bonded connector pins in comparison to the elliptical vibration mode. For the multi-frequency vibration mode, the most homogeneous interface was found. Whether bonds made using the multi-frequency vibration mode increase reliability should be investigated in future work.

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