Smart Ultrasonic Welding in Power Electronics Packaging

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Abstract

Ultrasonic metal spot welding is a standard technology used in power electronics packaging, mostly for welding power terminal connectors to direct bonded copper (DBC) substrates. Ultrasonic wire bonding is a very similar technology, yet there are significant differences regarding processes, applications, and available equipment. Production equipment combining the ultrasound power of welders with the flexibility, precision, and process control of wire bonders into a “smart welding process” is highly desired. This contribution compares the technologies and presents process results for a cylindrical cell battery pack. They highlight the advantages of smart over classic ultrasonic welding and demonstrate that smart ultrasonic welding and wire bonding have individual strengths and weaknesses.

1 Ultrasonic welding and wire bonding in power electronics

The two technologies of ultrasonic metal spot welding and ultrasonic wire bonding are both commonly used in power electronics packaging. There are many principal similarities between the two, but also a number of practical differences regarding processes, equipment, and applications.

1.1 Ultrasonic metal spot welding

In ultrasonic metal spot welding, two (or more) metallic partners are joined in a discrete area. It is the most relevant ultrasonic welding technology in power electronics applications, other ultrasonic welding technologies join plastic parts and/or form continuous joints.

Machines for ultrasonic metal spot welding create mechanical vibrations with amplitudes of several µm in the low ultrasonic frequency range (typically 15 to 40 kHz), which are transmitted to the welding spot through a so called sonotrode. The contact partners are pressed between the vibrating sonotrode tip and a stationary (or passively vibrating [1, p. 263f]) support, often called anvil. Through the application of vibration energy under pressure, the two parts, which can be of dissimilar metals, are joined in a solid-state process, i.e. without melting [1].

The design of ultrasonic metal spot welding machines varies and so do the incorporated piezoelectric transducers which create the vibration. Commercially available machines can be classified into the five groups shown in **Figure 1**, with the classic and most common types being the “lateral drive” (A) and the “wedge-reed” (B) designs [1; 2, p. 138ff]. The machine designs have individual advantages and disadvantages. For example, machines with transverse contact vibration (types A, B, D, E) can suffer from “hammering”, undesired vertical vibration which can impair process stability and damage the substrate. This can usually be compensated by modification of the mechanical setup and parameterization of the process. On the other hand, machines with torsional contact vibration principally suffer from the fact that there is no vibration amplitude in the center of the contact, and thus often insufficient joining.

Ultrasound transducer and sonotrode usually only have a vertical degree of freedom, so the products to be welded must be placed underneath the welding tip with the correct orientation. The welding tool tip must be large enough to cover manufacturing and placement tolerances and sufficient space must be provided in product design. The normal force is commonly applied pneumatically, sometimes hydraulically or electromagnetically. Some machines with off-axis force application apply a torque to the sonotrode instead of a force in order to generate the required contact force. **Figure 2** shows a typical machine used for ultrasonic metal spot welding, which uses torsional sonotrode vibration to create a quasi-transverse vibration at the welding spot (type E in **Figure 1**).

Typical ultrasonic metal spot welding machines provide ultrasound powers of 0.5 to 10 kW at frequencies between 15 and 40 kHz, with the corresponding normal force reaching up to 10 kN. Contact areas of up to 100 mm² can be welded at sheet thicknesses of up to 5 mm.

1.2 Ultrasonic heavy wire bonding

Ultrasonic wire bonding is a standard technology used to produce electrical interconnections in micro and power electronics [4]. An automatic ultrasonic wire bonder supplies a wire with round or rectangular cross-section (ribbon) from a spool and the wire is welded (“bonded”) to a defined first position. The machine then forms a wire loop by moving the bond head following a defined trajectory, bonds the wire to a second position and finally severs the wire. **Figure 3** shows a snapshot of a heavy wire bonding process between first and second bond.

Automatic wire bonding machines can precisely move and rotate the ultrasound transducer with the bonding tool. The machine can thus produce multiple connections at different locations, orientations and heights within one or multiple products, without the products being moved. This allows tight spacing and thus compact products. Linear motor

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driven kinematics enable precise and fast movements, resulting in high speed processes with multiple wire bonds per seconds. The normal force is applied by a precise electromagnetic actuator, allowing the normal force to be controlled and changed dynamically during the bonding process.

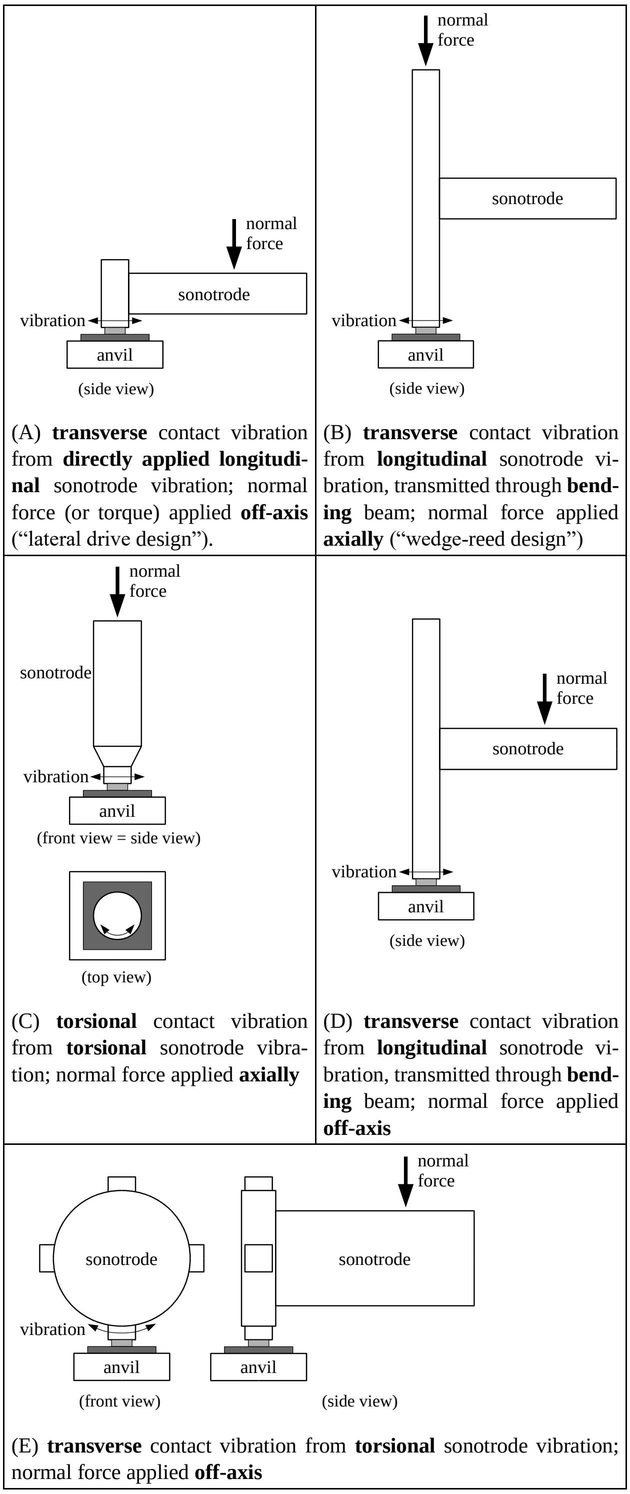


Figure 1 Types of ultrasonic metal spot welding machines

The bonding process itself is principally a very low power ultrasonic metal spot welding process using a machine with transverse vibration transmitted through a bending beam (type D in **Figure 1**), the physical joining process is identical. For this reason, ultrasonic wire bonding is sometimes called “ultrasonic micro welding” [5]. In microelectronic applications, wire bonding uses about 1 W of ultrasound power at frequencies between 60 and 150 kHz. Typical wire bonding machines for power applications work with maximum nominal powers of 100 W at frequencies between 40 and 100 kHz. Depending on material, these machines can process round wire diameters of up to 600 µm and ribbon cross-sections up to 400 x 2000 µm². Typical materials are Al, Cu, and Al-clad Cu.

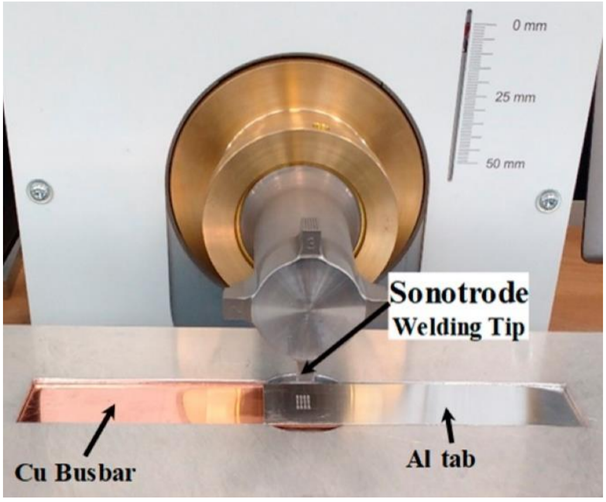


Figure 2 Ultrasonic metal spot welding using a Telsonic MPX machine, working at 20 kHz with a maximum power of 6.5 kW (image from [3], used under license CC BY 4.0, cropped and label removed)

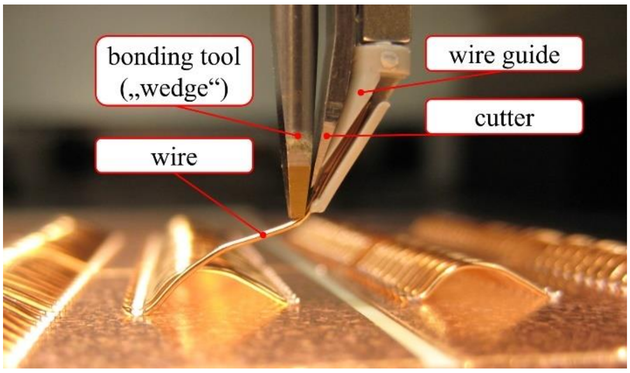


Figure 3 Heavy copper wire bonding on test substrate

An automatic ultrasonic wire bonding machine could thus be described as a conventional ultrasonic spot welding machine with low power and extended functionality. This includes fast and precise movement of the transducer in four axes, freely programmable courses of ultrasound vibration amplitude and normal force, and supplying, forming, and severing the wire. Current automatic wire bonding machines also include advanced functions not common to metal spot welding equipment. Some of these functions, such as pattern recognition, touchdown sensing, and normal force control, are mandatory to produce reliable connections between the small wires and the often sensitive substrates. Other features, such as diverse advanced process control functions, standardized interfaces for assembly line integration, and the flexibility to handle a large variety of products and layouts with one series machine by a mere change of clamping and programming, provide the user with increased control and flexibility.

1.3 Applications in power electronics packaging

Typical power electronics packaging applications for ultrasonic metal spot welding are terminals and power contacts, e.g. in IGBT or inverter modules, as well as busbar connections. Such ultrasonic welding is only used on robust passive material such as DBC and terminals, while heavy wire bonding is also commonly used to produce connections on sensitive active substrates such as chips, even with hard wire material such as copper [6, 7]. In fact, many power modules use wire bonding for internal connections, e.g. die to die, die to DBC, and higher power ultrasonic welding for connecting the external power contacts. **Figure 4** shows an example of such a combination. Wire bonding is also increasingly used in the production of Li-ion battery packs [8].

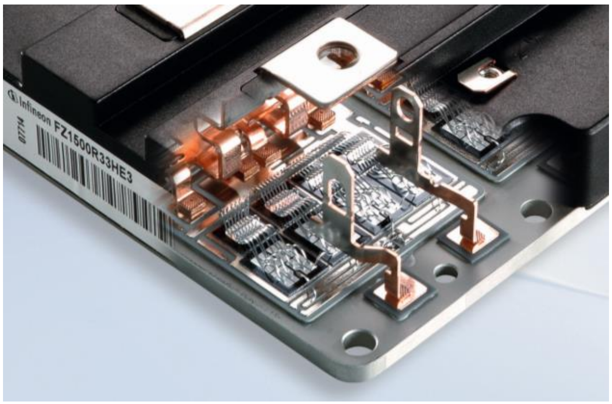


Figure 4 Section of a power module combining Al wire bonds and ultrasonically welded Cu power contacts (image courtesy of Infineon Technologies AG)

1.4 Quality control

Besides optical inspection, destructive and non-destructive mechanical tests like shear, pull, or peel tests are classic methods to evaluate the joint quality of ultrasonic processes. Online observation of certain parameters over the course of the welding time is nowadays also common in classic ultrasonic welding and standard in wire bonding. The following quantities are often evaluated:

- Electric current (if voltage is set) or voltage (if current is set) amplitude or impedance (relation of voltage to current)
- Electric power or energy
- Vertical deformation
- Vibration frequency (if resonance frequency tracking is used)

Current, voltage, impedance, power, and energy are not independent quantities. Current, voltage, or impedance are commonly observed in wire bonding, while power or energy are more common in ultrasonic welding. If any of the observed quantities are outside certain limits, a joint is regarded as suspicious. Such tests do not consume any time and can thus be applied to 100 % of the joints. As tests have shown that not all bad wire bonds could be identified using current and deformation alone [9, 10], frequency observation is very common in wire bonding nowadays. Still, this does not guarantee identification of all potentially bad welds. Thus, more advanced quality control systems use additional independent quantities to determine joint quality.

One such system, productively used in wire bonders for several years, is the multidimensional Process integrated Quality Control (PiQC) [9, 10]. Using an additional sensor integrated into the ultrasound transducer, it evaluates five different physical quantities over the whole length of the process: mechanical vibration of the welding tool, friction in the welding zone, wire deformation, transducer impedance, and operation frequency, i.e. transducer resonance frequency. From their course over the process time, it calculates quality indices for each of these quantities based on a previously learned set of reference welds representing a good, stable process. This process automatically excludes outliers. The quality indices are calculated based on the deviation of each signal from the reference course, weighted by a learned statistical model of the individual process, using user-defined tolerance and sensitivity settings as shown in **Figure 5**. For each connection, a total quality index is calculated from the five individual quality indices. A user-defined action limit is applied to the quality index. All these calculations happen in real-time and do not affect the total process time.

A low quality index does not necessarily mean that a connection is bad, but that it is significantly different from the reference. But if this reference is a good, stable process producing optimum results, any deviation is very likely to indicate a bad connection. This method is able to detect failures such as incorrect tool mounting, contaminations, or misplaced welds, even if they were not detected by classic destructive testing such as shearing [9, 10].

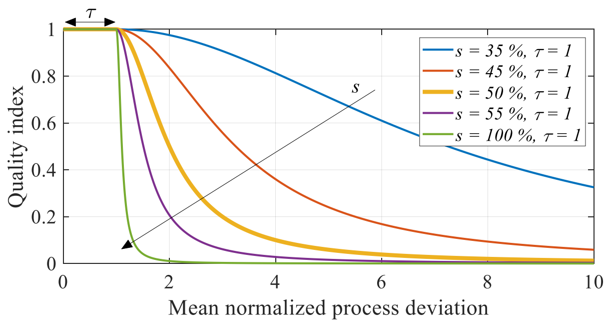


Figure 5 Calculation of individual quality indices from mean signal deviation relative to the learned statistical model for the individual process, using parameters sensitivity s (default 50 %) and tolerance default $\tau = 1$.

2 Smart ultrasonic welding

In principle, most wire bonding machines could be programmed to not use the wire handling functions and work as an ultrasonic welding machine with advanced functionality. But in such a scenario, the unused wire handling components would produce unnecessary costs and limit accessibility. Also, the maximum power of heavy wire bonders is too low for most current ultrasonic welding applications. Thus, there is a need for machines for what we call "smart ultrasonic welding", combining the force and ultrasound power of conventional ultrasonic welding machines with the flexibility, precision, speed and process control features of state-of-the-art wire bonding machines.

These include precise positioning and rotation, pattern recognition to detect the exact weld location, and derivation of an optimal trajectory to reach the weld location quickly and very precisely. Together with long and slim welding tools, this allows flexible layouts and very tight spacing, and thus more compact products or higher power density in existing packages. Touchdown sensing, freely programmable ultrasound and force courses, and precise contact force control facilitate welding on sensitive substrates. Like ultrasonic wire bonders, smart welding machines can flexibly handle a large variety of products.

3 Case study: interconnections in cylindrical cell battery packs

As a case study, we present and compare wire bonding and (smart) welding processes for a battery pack application. Ultrasonic joining has some advantages over other technologies for such applications. It does not require zero gap between lead frame and cell like laser welding as gaps are closed automatically during the application of the initial normal force, and it can handle high tolerances in height, position and orientation. It is insensitive to varying reflectivity or high thermal conductivity and has little heat effect and no heat affected zone, other than laser and resistance welding. And it produces neither smoke nor splatter. The main disadvantages of ultrasonic joining over these technologies are that it requires clean surfaces of constant quality and that the parts to be joined must be properly fixed for a reliable process.

The case study was conducted using a Hesse Mechatronics SW955 (type D machine design, cp. **Figure 1**). This machine with a maximum ultrasound power of 200 W is capable of welding copper contacts up to about 2 mm² and marks the low power end of a series of smart welders. This machine series shall provide producers of medium-sized ultrasonically welded connections with increased process control and freedom of design for the next generation of power electronics, battery packs and other applications. Thy hybrid machine used for the tests handles both smart welding and wire bonding.

The power connections in the investigated battery pack have been produced using 500 µm Al (Heraeus Al-H11 CR) wire bonds and ultrasonic welds of pre-placed Al (EN AW-Al 99.5 H12) lead frames. A third option for such an application, not investigated here, is ribbon bonding, i.e. wire bonding with rectangular cross-section wire. The pack uses 4 x 6 passive ("dummy") cells of size 21700 (21 mm diameter, 70 mm height) in a 6p4s configuration (6 cells in parallel, 4 in series), resulting in a pack voltage of 4 x 3.6 V = 14.4 V if real cells were used. It was developed by Hesse Mechatronics for demonstration purposes. Cap and crimp of the cells are made of nickel-coated steel, bus bars between the cells are made of AlMgSi0.5.

3.1 Connection layout

Referring to the top views in **Figure 6**, the produced interconnections connect the caps (positive electrodes) of the cells to the bus bar above and the crimps (negative electrodes) to the bus bar below. Thus, 48 weld connections are needed to connect the 24 cells with pre-placed lead frames, cp. **Figure 7(a)** and **Figure 6(a)**. With wire bonding, lead frames are obsolete, but the connecting wire must also be bonded to the bus bar. So called stitch bonds are used to connect inner bus bars with a cap and a crimp using a single wire and three bond connections. Thus, in this pack configuration with four rows of six cells each, a total of 78 bond connections is needed – 24 on caps, 24 on crimps, 30 on bus bars, cp. **Figure 7(a)** and **Figure 6(b)**. With increasing pack size, the share of inner bus bars increases, reducing the share of single-connection wire bonds. The number of bonds per cell is $3+1/n$, with the number of rows of cells n. It is thus 3.25 in this example with $n = 4$ and approaches, but never reaches, 3.

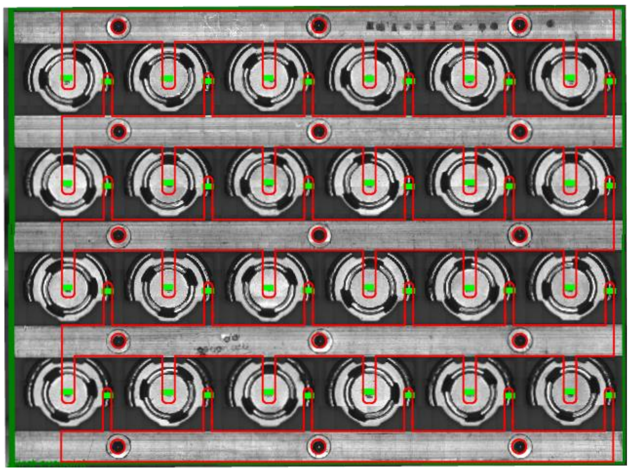
In the welding process, any layout change requires a modification of the lead frame. With wire bonding, layout changes can be implemented in the bonding program within minutes.

3.2 Pattern recognition

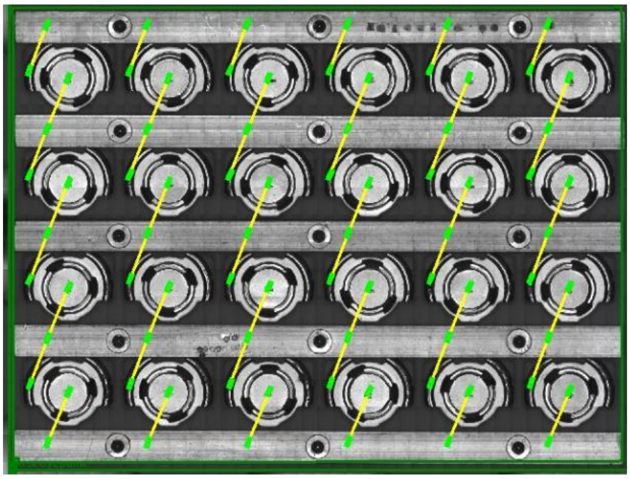
Positioning accuracy requirements in battery pack manufacturing are typically less tight than in electronics manufacturing. Still, the connections must be placed at the correct positions to ensure a stable manufacturing process and electrical functionality of the pack. This is true for both (smart) welding and wire bonding.

In this use case, the positions of welds and wires were defined relative to the edges of the battery pack. Before welding a pack, its position is detected by pattern recognition of two corners. If necessary, e.g. in battery packs manufactured with less accuracy or if a very constant process result is desired, pattern recognition can also detect the individual cells, but this takes more time and reduces throughput. **Figure 6** shows the bonding/welding patterns as defined after pattern recognition.

Power electronics packages designed for classic ultrasonic metal spot welding often include large clearance to compensate for coarse positioning of the product under a rather bulky stationary welding tip. With pattern recognition and precise positioning available in smart welders, these clearances can be minimized, enabling more compact designs.



(a) smart welding process



(b) wire bonding process

Figure 6 Screenshots showing positions of planned welds (green) and wires (yellow) after the pack position has been detected by pattern recognition; smart welding screenshot augmented with overlay of lead frame contours (red).

(a) (b)

Figure 7 Details of battery packs produced by (a) welding of pre-placed lead frames, (b) wire-bonding

3.3 Process time

Because welding with pre-placed lead frames requires less welds and no looping or cutting, process time excluding the welding process is much shorter, with 6.8 s for smart welding and 15.9 s for wire bonding on a Hesse Mechatronics SW955 operating at full speed with the same typical settings for touchdown velocity and height.

The required welding times are highly dependent on the materials of the contact partners and on the vibration characteristics of the substrates, they can differ by 100 % and more. The materials used in this case study were not ideal, thus the achieved welding times are longer than what can be expected for a well-developed industrial process and not suitable for a realistic comparison. Especially the material of the lead frame appeared to be critical.

Assuming welding times of 0.3 s for cap and crimp connections and 0.15 s for the simpler (Al on Al, rigid substrate) bus bar connections, an industrial smart welding process would take 21.2 s, while wire bonding would take 34.8 s, i.e. 64 % longer. But any comparison must consider the longer process chain of smart welding, including lead frames placement, and the desired tact time in relation to automation and loading. A practical comparison should also always use real welding times and consider required contact areas. In the investigated example, wire bond contact areas are about 0.5 mm², while lead frame welds are about 1.3 mm².

3.4 Quality control

As an example, the PiQC system described in section 1.4 has been applied to the 24 cap welds with the tolerance τ set to 0 for demonstration purposes. A tolerance setting of $\tau = 0$ means that even the smallest deviation from the learned reference results in a quality index below 100 %, cp. **Figure 5**. This is not practical for productive use, but makes the variation within the group of good welds visible, which would otherwise all have a quality index of 100 %. **Figure 8** shows the calculated total quality indices. The threshold was set to 50 %, thus the system in production mode would identify one weld (with quality index 48.8 %) as “bad”, marked in yellow in **Figure 8**.

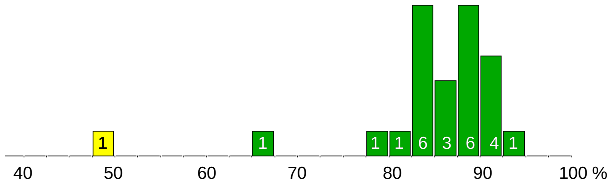


Figure 8 Histogram of calculated total quality indices of cap welds, with sensitivity s = 50 % and tolerance $\tau = 0$.

Looking at the individual quality indices, cp. **Figure 9**, it becomes obvious that the main driver for identification of the weld as “bad” is its poor wire deformation quality index of almost 0, but that its other quality indices are also at the lower edge of the investigated set. In fact, the raw wire deformation signal, cp. **Figure 10**, shows a significantly different course especially in the second process phase (after 0.5 s). Other deviations leading to low quality indices can be much less obvious, but still indicate a significantly different, i.e. worse, process result. This example demonstrates that Process integrated Quality Control provides a reliable and time-efficient non-destructive method for 100 % quality control in smart ultrasonic welding equipment.

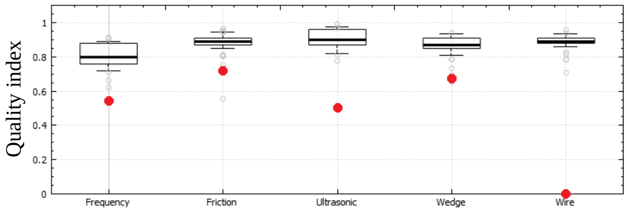


Figure 9 Boxplots of individual quality indices, with the "bad" weld marked in red

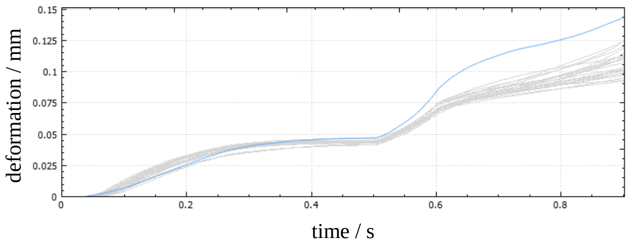


Figure 10 Vertical deformation of all 24 welds over weld time, with the "bad" weld marked in blue

4 Conclusion and outlook

In this contribution, we compared the ultrasonic joining technologies of classic ultrasonic spot metal welding, wire bonding, and smart welding and investigated their feasibility power electronics packaging, as opposed to classic ultrasonic metal spot welding. Smart welding machines provide a significant advantage over classic ultrasonic metal spot welding equipment regarding flexibility, precision, speed and process control. In these regards, including advanced quality control, smart welding is on par with wire bonding.

We also smart welding and wire bonding in a battery pack case study conducted on a hybrid machine. The study has shown that battery packs can be produced using smart ultrasonic welding as well as using ultrasonic wire (or ribbon) bonding. Both types of machines provide identical features. Some machines, like the one used for the case study, even handle both processes. For these reasons, the process itself is what makes one or the other the better choice for a specific industrial application.

Wire (and ribbon) bonding processes do not require a pre-placed lead frame. This saves the production of this part and the placing process. It also results in a higher flexibility of the bonding process, as layout changes can be realized by mere programming. On the other hand, process time (without placing) for welding with pre-placed lead frame typically is significantly lower. Lead frames can be designed to have more or less any contact area, while wire bonding can scale the contact area by the number of wires and their size, limited by wire handling.

Both processes can profit of the addition of heat to the process, which can increase weld strength and/or reduce process time. It can also increase bondability and enable processes using materials not feasible at room temperature. While substrate heating is impractical for battery applications and many others, direct heating of the process zone using laser power has recently been demonstrated successfully [11, 12] and is expected to soon be available in commercial equipment.

5 Literature

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