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Smart Ultrasonic Welding – A Versatile Interconnection Technology for Power Electronics Packaging

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Abstract

Ultrasonic welding is a common and indispensable technology in the packaging of power electronics. Typical applications are terminals and power contacts, e.g. in motor drive or inverter modules, as well as busbar connections. The process control requirements for welding power electronics connectors or bus bars, e.g. on batteries, are increasingly overlapping with requirements typical for heavy wire bonding. Smart ultrasonic welding is a new technology combining the force and ultrasonic power of conventional ultrasonic welding equipment with the flexibility, precision, speed and advanced process control features of wire bonding machines.

This contribution discusses the characteristics of smart welding equipment and presents process results for two different smart welding applications. On the low power end, smart welding and wire bonding are compared in the production of cylindrical cell battery packs, using a 100 W ultrasound system and aluminium connectors. Towards the high power end, 3 x 1.2 mm² copper leads are welded to DBC with a contact area of 3 x 3 mm², using a 1.5 kW ultrasound system. Both applications demonstrate advantages of smart welding over conventional ultrasonic welding.

Key words

smart welding, wire bonding, ultrasonic welding, power connectors, battery pack manufacturing, power electronics

I. Introduction

Ultrasonic welding is a common and indispensable technology in industrial production, used for products as diverse as large automotive plastic parts, packaging foils and stranded wires. For many years, ultrasonic metal spot welding is also being used in the packaging of power electronics.

As the power electronics market and related applications have grown since, process control requirements for welding connectors or bus bars, e.g. on batteries, are increasingly overlapping with requirements typical for heavy wire bondi#ng. Hence, for some applications both technologies are evaluated, despite some obvious differences between equipment for conventional ultrasonic metal welding and ultrasonic wire bonding:

- Ultrasonic metal welding uses ultrasonic powers between about 500 W and several kW, while ultrasonic wire bonding machines typically provide 100 W of ultrasonic power or less. As a consequence, copper ribbon bonding is limited to maximum contact areas below 2 mm² while ultrasonic welding machines can handle tens of mm².
- Ultrasonic metal welding equipment typically works at low ultrasonic frequencies of about 20 to 40 kHz, while ultrasonic wire bonding uses frequencies of about 40 to 150 kHz, depending on application. At lower frequencies, higher mechanical amplitudes are necessary to provide the same ultrasonic power.
- As a consequence of higher power and lower frequency, ultrasonic metal welding equipment uses much larger ultrasound transducers and uses higher mechanical amplitudes than wire bonding equipment.
- The employed welding tools differ also in size and shape: While the shape of welding sonotrodes depends on the design and operation principle of the ultrasound system [1], they are generally thick and rather compact. Bonding wedges are long and slender, which enables wire bonding inside tight cavities and with smallest pitches.
- In conventional ultrasonic metal welding, the normal force is applied pneumatically. Wire bonding machines have a linear motor driven kinematic and a sensitive

overtravel mechanism with a dedicated actuator for normal force control, allowing the normal force to be changed dynamically during the bonding process.
- Conventional ultrasonic metal welding equipment has a stationary ultrasound transducer. The product must be placed underneath it to be welded. Automatic wire bonding machines move and rotate the ultrasound transducer very precisely. Fast image recognition determines the exact bond locations, which are reached quickly and precisely following a calculated optimal trajectory. This allows very tight spacing and thus compact products.

As a consequence of the above-mentioned differences, conventional ultrasonic metal welding is only used on robust passive material such as DBC and terminals; still cratering or power-cycling failures can be an issue. In contrast, heavy wire bonding is also commonly used to produce reliable connections on sensitive active substrates such as chips, even with hard wire material such as copper [2, 3]. In fact, many power modules use wire bonding for internal connections, e.g. die to die, die to DBC, and ultrasonic welding for connecting the external power contacts. **Figure 1** shows an example of such a combination. Wire bonding is also increasingly used in the production of Li-ion battery packs [4].

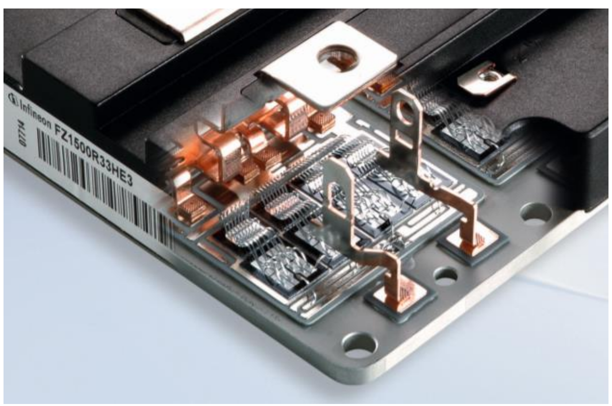


Figure 1 *Section of a power module combining Al wire bonds and ultrasonically welded Cu power contacts (image courtesy of Infineon Technologies AG)*

II. Quality Control in Ultrasonic Joining

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.

Commonly evaluated quantities are electric current or voltage amplitude or impedance (relation of voltage to current); electric power or energy; vibration frequency (if resonance frequency tracking is used); vertical deformation. Current, voltage, or impedance are commonly observed in wire bonding, while power or energy are more common in conventional 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 and guarantee continuous traceability.

As tests have shown that not all bad wire bonds could be identified using current and deformation alone [5, 6], 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, like an additional sensor integrated into the ultrasound transducer [5, 6].

One example for such a system is the multidimensional Process integrated Quality Control (PiQC), which has been productively used in wire bonders for several years. 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. For each connection, a total quality index is calculated from the five individual quality indices. **Figure 2** shows an example of these quality indices.

All these calculations happen in real-time and do not affect the total process time. This system detects failures such as incorrect tool mounting, contaminations, or misplaced welds, even if they are not detected by classic destructive testing such as shearing [5, 6].

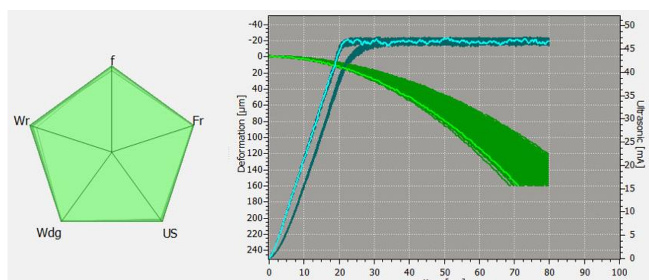


Figure 2 *(left) Quality radar chart showing the five individual PiQC quality indices and (right) courses of wire deformation (green) and ultrasonic current amplitude (blue) over time. Screenshot from the user interface of a Hesse Mechatronics BJ959 wire bonder.*

III. Smart Ultrasonic Welding

Ultrasonic Welding and Wire Bonding are less different than they seem at first glance. In both cases, two metallic partners are connected without melting by interdiffusion and formation of intermetallic compounds induced by ultrasonic vibration. An automatic wire bonding machine supplies the wire which it then bonds to a defined first position, forms a wire loop by moving the bond head following a defined trajectory, bonds the wire to a second position and severs the wire by cutting or tearing. An automatic ultrasonic wire bonding machine could thus be described as a conventional ultrasonic welding machine with extended functionality. Further advanced functions include image recognition, touchdown sensing and normal force control, diverse process and quality control features, and standardized interfaces for assembly line integration. The standardized designs of ultrasonic wire bonders can flexibly serve a large range of applications. Adaption to new products or new variants is achieved with minimal effort regarding welding tools and automation.

Thus, a wire bonder with removed wire handling functionality and increased ultrasonic power can be called a “smart ultrasonic welding machine”. Such machines, which also include advanced quality control systems as described above, have recently been introduced to the market. In the following, we present process results for two different smart welding applications.

IV. Cylindrical Cell Battery Pack

As a case study with a typical low-power application, we compare smart welding to wire bonding in the production of cylindrical cell battery packs, using aluminium connectors and a 100 W ultrasound system [1]. Ultrasonic joining has some general 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. It also produces neither smoke nor splatter. Other than these technologies, ultrasonic joining requires clean surfaces of constant quality and the parts to be joined must be properly fixed for a reliable process.

The case study was conducted using a Hesse Mechatronics BJ/SW955. This machine with a maximum ultrasonic power of 200 W is capable of welding copper contacts up to about 2 mm². The hybrid machine used for the comparison handles both smart welding and wire bonding.

The power connections in the investigated battery packs have been produced using 500 µm Al (Heraeus Al-H11 CR) wire bonds or 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, developed by Hesse Mechatronics for demonstration purposes, 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). Cap and crimp of the cells are made of nickel-coated steel, bus bars between the cells are made of AlMgSi0.5.

A. Connection layout

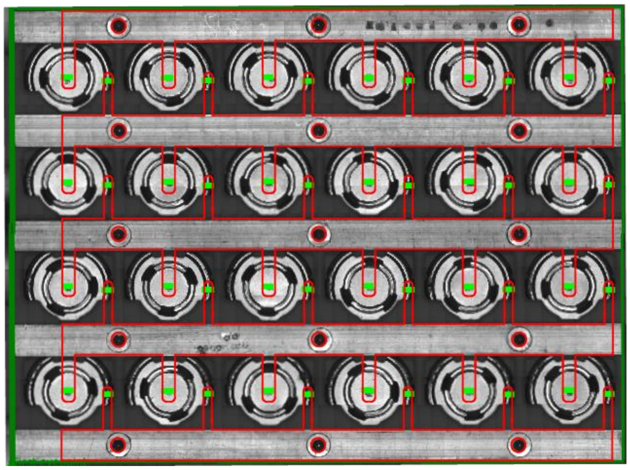
Referring to the top view in **Figure 3**, the produced interconnections connect the caps (positive electrodes) of the cells to the bus bar above and the crimps (negative electrodes) to the bus bar below. Thus, 48 weld connections are needed to connect the 24 cells with pre-placed lead frames, cp. **Figure 4(a)** and **Figure 3(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 4(a)** and **Figure 3(b)**.

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.

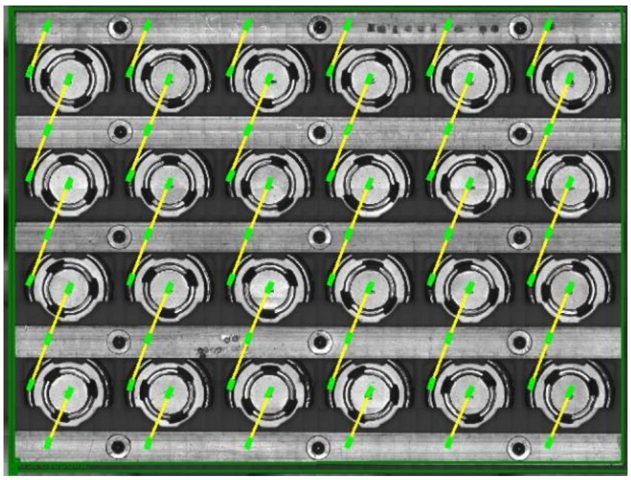
B. Pattern recognition

Positioning accuracy requirements in battery pack manufacturing are typically less tight than in electronics manufacturing. Still, to ensure a stable manufacturing process and electrical functionality of the pack the connections must be placed at the correct positions, especially on the narrow cell crimp. 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 3** shows the bonding/welding patterns as defined after pattern recognition.



(a) smart welding process



(b) wire bonding process

Figure 3 *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 4 *Details of battery packs produced by (a) welding of pre-placed lead frames, (b) wire-bonding*

C. 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 hybrid 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 challenging.

Assuming typical 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, cf. **Figure 5**. But any comparison must consider the longer process chain of smart welding with potentially higher cost, 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. Larger contact areas are possible with both technologies; ribbon bonding uses contact areas up to about 3.3 mm².

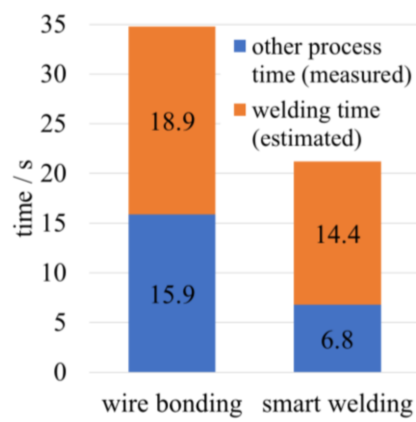


Figure 5 *Cycle time for one battery pack*

V. Power Connectors on DBC

To demonstrate the capability in mid-power applications, smart welding was used to connect 3 x 1.2 mm² leads of ETP (electrolytic tough pitch) copper to a DBC (direct bonded copper, also called DCB – direct copper bonding) test board with a contact area of 3 x 3 mm². The board consists of 0.38 mm thick Al_2O_3 between two 0.3 mm layers of Cu-OF (oxide free). Such connections are produced by conventional ultrasonic welding in industrial applications, with typical vibration amplitudes of 30 µm peak at 20 kHz.

Compared to smart welding, this process is rather slow and inflexible. It can produce different types of failures, which we investigate in the following, and which can reduce process yield.

The welds were made on a Hesse Mechatronics SW1185 with a 1.5 kW 20 kHz ultrasound system. Six leads were welded in a row, **Figure 6** shows one such row. For comparison, the same copper leads were also welded with the same ultrasound system on a test rig. It is similar to a smart welder, but lacking some of its features, and shall represent a simple ultrasonic metal welding system. Specifically and in contrast to a smart welder, the test rig has no pattern recognition system, cannot stop after a certain vertical deformation and has no advanced force control, i.e. it provides a set normal force without ramps, which decreases as the lead deforms.

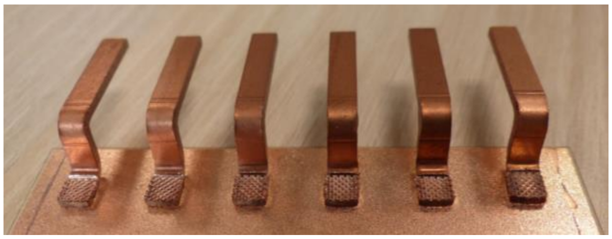


Figure 6 *One row of welded copper leads*

A. Effect of pattern recognition

The six leads are placed in a row, but their positions vary slightly. This is due to the manual placement in the test setup, but also typical for industrial applications. Conventional ultrasonic welding often uses tools much larger than the contact to be welded in order to compensate this positioning variation. This requires additional space around the weld location, which is why power electronics packages designed for classic ultrasonic metal spot welding often include large clearance. Smart welders with pattern recognition detect the individual lead positions precisely and can thus work with slenderer tools. **Figure 7** illustrates how pattern recognition places the welding tool perfectly centred on a lead, while an uncorrected offset results in uneven pressure distribution.

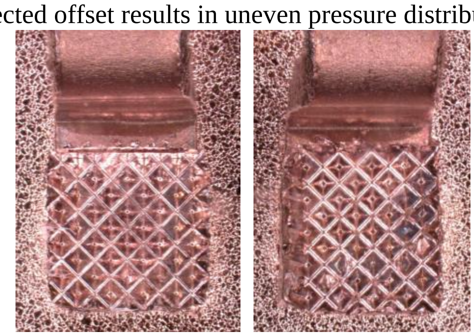
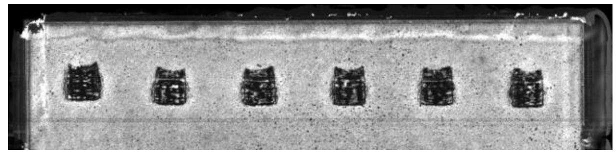


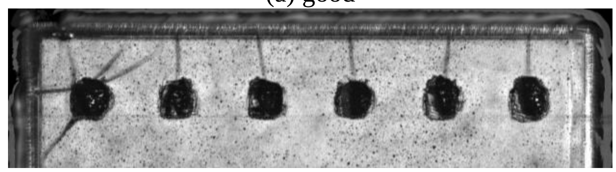
Figure 7 *Microscope images of slightly misplaced leads welded with pattern recognition (left) and without (right)*

B. Effect of force control

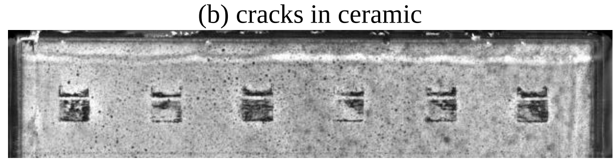
Controlled force application is crucial for successful, high-yield ultrasonic welding on crack-prone substrates such as DBC. On the smart welder, a controlled force can be gently applied using ramps, which results in strong welds with well-defined deformation of the copper leads and an intact DBC. (**Figure 8**(a)). For comparison, the same process parameters have been used on the test rig without sophisticated force control and deformation control. While this resulted in strong welds, but cracked DCB (**Figure 8**(b)), attempts to avoid these defects by reducing the ultrasonic power led to insufficiently bonded connections (**Figure 8**(c)).



(a) good



(b) cracks in ceramic



(c) insufficient bonding with reduced force and amplitude

Figure 8 *Surface acoustic microscopy (SAM) images of three rows of welded copper leads. (a) produced on a smart welder, (b) and (c) produced on a test rig without advanced force control. (a) and (b) used the same parameters, apart from force ramp and deformation-triggered stop.*

Several rows of leads were welded and the shear strength of the leads was tested using a xyztec shear tester, **Table 1** contains the test results. Welds with cracked ceramic (b) show a similar mean shear strength as good welds (a), but with a much higher deviation. As expected from the SAM images, insufficiently bonded welds (c) show a much lower shear strength, yet the relatively highest deviation. We conclude that SAM microscopy is important to detect possible cracks, shear tests can be an additional quality indicator.

Table 1 *Shear strengths of the three sets of welded copper leads*

set	number of welds	mean shear strength / N	std. dev. of shear strength / N
(a)	29	1304.7	78.4
(b)	18	1346.5	250.4
(c)	17	618.3	191.0

VI. Conclusion and Outlook

Smart welding is a technology intended to provide producers of small and 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.

In both applications presented in this contribution, we see advantages of smart welding over conventional ultrasonic welding such as reduced total process time, less required clearance, low variation, less risk of substrate damage and better process control through very fast and precise control of force and ultrasound trajectories, increased process flexibility including three-dimensional movements and rotation, and improved quality control.

The battery pack study has shown that such packs can be produced using smart ultrasonic welding as well as using ultrasonic wire (or ribbon) bonding. To determined which process is the better choice for a specific industrial application, it is necessary to look at the individual process, including necessary pre-processes, and the desired flexibility regarding design changes.

The study investigating power connectors on DBC has demonstrated that cracks, as an important failure mechanism on active/brittle substrates, can be avoided using the process control features of smart welders.

Both wire bonding and smart welding 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 [7-9] and is expected to soon be available in commercial equipment.

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