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Process advantages of thermosonic wedge-wedge bonding using dosed tool heating

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Abstract

Thermosonic wire bonding has a number of advantages over “cold” ultrasonic wire bonding. Despite these potential advantages, it is rarely used besides ball-wedge and gold wedge-wedge applications, mostly due to the drawbacks and limitations of available heating technology. A recently introduced novel thermosonic process using a laser-heated bonding tool avoids most of these drawbacks. This contribution presents the results of two series of bonding tests which have used this novel process to bond aluminium and copper heavy wire to sheets of the same metal.

The bond test results prove that thermosonic wedge-wedge bonding with a laser-heated tool has a number of significant advantages in both aluminium and copper wire bonding. It can be used to reduce the process time, to decrease the mechanical stress in the substrate by reducing ultrasound vibration amplitude and/or normal force, and to increase bond strength. These advantages are the same as in classic thermosonic wire bonding, but without the major disadvantage of having to heat to whole package. Because of the high thermal conductivity and capacity of the investigated metal sheet substrates, the observed positive effects of a heated tool are expected to be significantly higher on real-world substrates such as power semiconductors.

Key words

thermosonic bonding, laser heating, tool heating, wire bonding, Al wire, Cu wire

I. Introduction

Ultrasonic wedge-wedge heavy wire bonding is a well-established industrial process for electrical connections in power electronics [1, pp. 33-38]. Ultrasonic wire bonds are formed by interdiffusion and formation of intermetallic compounds induced by ultrasonic vibration [1, p. 24].

The vast majority of wedge-wedge wire bonds using aluminium or copper wire are produced at room temperature. For thin gold wire applications in both wedge-wedge and ball-wedge technology, it is common to heat the interface and the whole device to about 125 to 220 °C [1, p. 36]. Such a process, also increasingly used for copper wire ball-wedge bonding [2], is known as thermosonic wire bonding because it uses both thermal and ultrasonic energy.

In current applications of thermosonic wire bonding, heat is supplied through the workholder, which clamps the package containing the substrate to be bonded [1, p. 6]. Such a setup has significant drawbacks: The whole package is heated, thus it must be designed to withstand the increased temperature regarding material limits and thermomechanical stress, which is not possible in many applications. And it takes a certain time before the substrate has reached its target temperature and the bonding process can begin, which decreases throughput.

Heating time can be reduced and oxidation and thermal stress to the package can be avoided by not heating the whole package, but only the process zone. Different concepts for such a local heating have been investigated in the past and were reviewed by us in [3], but none of them is feasible in practical industrial heavy wire applications.

In [3], we have recently presented the concept of a novel thermosonic heavy wire and ribbon bonding process which uses a laser-heated bonding tool, the validation of the tool temperature control system and first bonding results using 500 µm copper wire. This thermosonic bonding process can use ultrasonic and thermal energy in a reproducible, user-definable composition to achieve optimal connections. Due

to the high power of the laser and the high absorption of the laser beam at the bonding tool, it is heated very quickly.
This contribution presents the results of two more extensive series of bonding tests using aluminium and copper wire, both 500 µm thick, using the novel thermosonic bonding process.

II. Advantages of Thermosonic Bonding

In thermosonic bonding, some of the activation energy required for interdiffusion of the bonding materials is provided in the form of thermal energy instead of kinetic ultrasonic vibration energy [1, pp. 33-36]. In some gold wire applications, especially where normal force and/or vibration amplitude are limited by the substrate sensitivity, this is necessary to obtain reliable bonds. Bonding at elevated temperature has several additional effects which can be positive also when processing other materials:

- Diffusion, a major driver of the bonding process, is accelerated at higher temperature. This can reduce the required process time.
- Increasing temperature reduces wire material strength and reduces or eliminates strain hardening [4]. Thus, the same wire deformation can be obtained with less normal force. This is particularly advantageous on sensitive substrates such as dies or sensors, where too high normal force is known to contribute to cratering [1, p. 256].
- Increased ultrasonic vibration has a similar effect on the stress-strain curve as increased temperature [5]. Thus, the same process potentially requires less vibration if run at an increased temperature. This, too, is particularly advantageous on sensitive substrates.
- The effects of substituting vibration energy by thermal energy can also be exploited to process wires which would require normal forces or vibration amplitudes beyond the substrate limits at room temperature. Examples for such systems are heavy copper wire bonds on sensitive silicon chips without special metallization [6], [7], but also ball bonds on thin microelectronic structures [8].
- Some material combinations, such as the aforementioned gold on gold, or aluminium on silver [1, p. 37], can only be reliably bonded at increased temperatures.

Despite these advantages, thermosonic bonding is rarely used besides ball-wedge and gold wedge-wedge applications, mostly due to the drawbacks and limitations of available heating technology. The novel thermosonic process using a laser-heated bonding tool avoids most of these drawbacks. The main aim of this contribution is to verify whether the above-mentioned advantages can also be observed with this novel thermosonic process.

III. Test Setup

The test setup is based on a Hesse Mechatronics Bondjet BJ959 automatic bonding machine. In order to provide the heating laser energy to the process zone, a near infrared laser source has been integrated into the bonding machine. An optical fibre is connected to the laser source and guides the laser to a focussing optic, which is attached to the bond head as shown in Fig. 1. It focusses the laser beam onto the tip of an otherwise standard bonding tool for 500 µm wire. Thereby, its heating power acts close to the bonding wire. All tests were performed with equal bonding tools for 500 µm wire.
The temperature of the tool tip is measured pyrometrically, with the pyrometer projected coaxially into the laser beam by a beam splitter to combine temperature measurement and laser heating in one optical fibre. The pyrometer is connected to an external controller, which, by measuring and controlling the tool tip temperature by adjusting the laser power, ensures a constant tip temperature, which is a prerequisite for a consistent quality of bond connections.

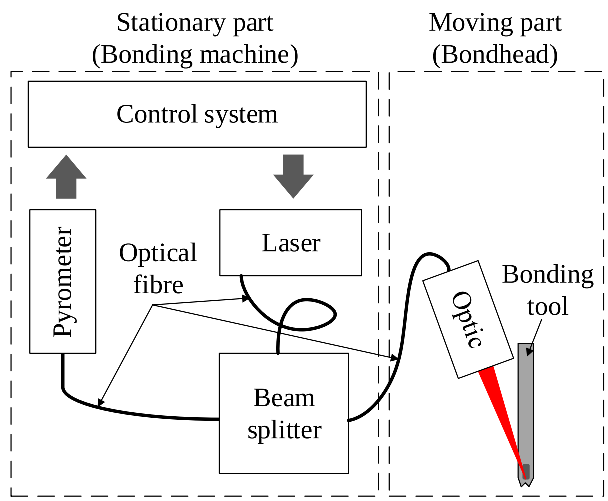

Fig. 1: Schematic of the test setup

IV. Test Results

A. Aluminium wire

500 µm aluminium wire (Heraeus AL-H11) single bonds, i.e. without wire loop, were placed on aluminium sheets sized 175 x 125 x 1.5 mm³. 25 bonds were evaluated for each parameter set.
First, a parameter set commonly used for bonding at room temperature was used. It is visualized in Fig. 2. Relative ultrasound and normal force variations described in the following maintain the course of the respective parameter over time, but scale its values by a constant factor. Bonding time variations maintain the courses of ultrasound and force; if necessary, ramps of either parameter are adjusted to reach their final value in the given total bonding time.

With this parameter set, bonds were produced with the tool at room temperature and with the tool heated to 430 °C. The results of a variation of ultrasound voltage and bonding time documented in Fig. 3 and Fig. 4 show that, with this parameter set, heating the tool increases the shear force in all investigated cases. It also allows to reach the same shear force in a shorter time or with less ultrasound.

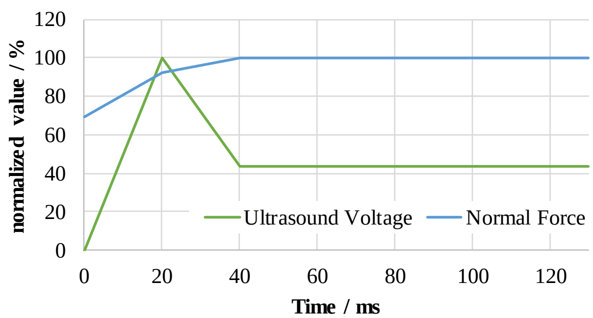

Fig. 2: Course of normalized ultrasound voltage amplitude and normal force in parameter set 1

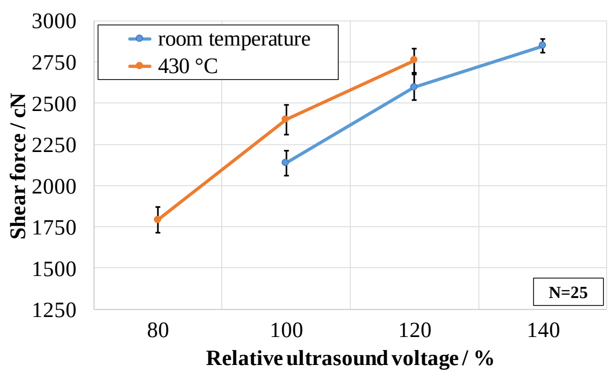

Fig. 3: Mean shear force of Al bonds made with parameter set 1 and varied ultrasound voltage, with the bonding tool at room temperature (RT) and at 430 °C; error bars indicate standard deviation.

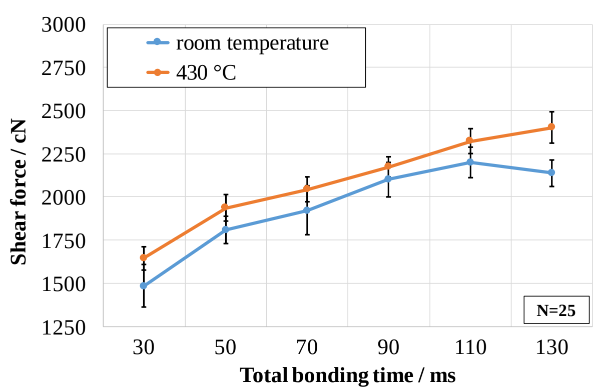

Fig. 4: Mean shear force of Al bonds made with parameter set 1 and varied bonding time, with the bonding tool at room temperature (RT) and at 430 °C; error bars indicate standard deviation.

In order to determine the time saving potential of thermosonic bonding, a parameter set optimized for bonding at a tool tip temperature of 430 °C was developed. It is visualized in Fig. 5.

With these parameters, a qualitatively same, but quantitatively larger effect as with parameter set 1 is observed, as documented in Fig. 6 and Fig. 7. For example, bonds created with parameter set 2 at 430 °C with 80 % ultrasound in 45 ms (equalling an integral of normalized voltage over time of 35.7 ms) show an even slightly higher mean shear force of 2225 cN than bonds created with parameter set 1 at room temperature with 100 % ultrasound in 130 ms (normalized voltage integral 63.9 ms), with similar standard deviation.

Fig. 6 and Fig. 7 also show the mean shear residue. Fig. 8 shows images of some shear residue samples. For any bonding time, the residue of bonds made at 430 °C is larger than that of bonds made at room temperature.

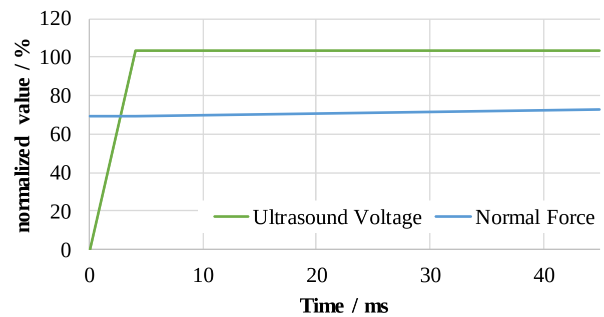

Fig. 5: Course of normalized ultrasound voltage amplitude and normal force in parameter set 2 (same normalization as Fig. 2)

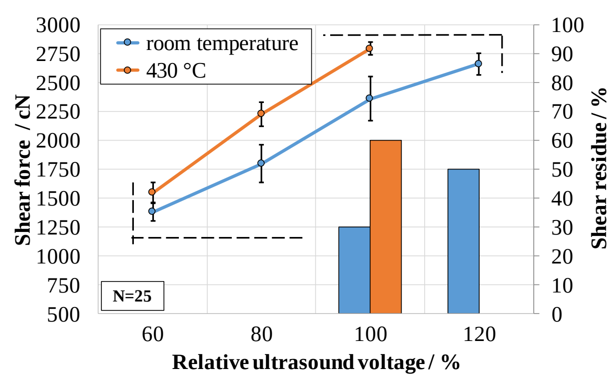

Fig. 6: Mean shear force and residue percentage of Al bonds made with parameter set 2 and varied ultrasound voltages, with the bonding tool at room temperature (RT) and at 430 °C. Error bars indicate standard deviation. Dashed line marks the parameter window in which neither non-sticks nor tool-substrate contacts appear.

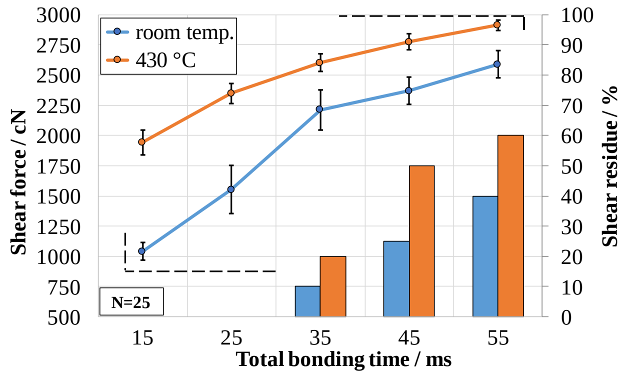

Fig. 7: Mean shear force and residue percentage of Al bonds made with parameter set 2 and varied bonding time, with the bonding tool at room temperature (RT) and at 430 °C. Error bars indicate standard deviation. Dashed line marks the parameter window in which neither non-sticks nor tool-substrate contacts appear.

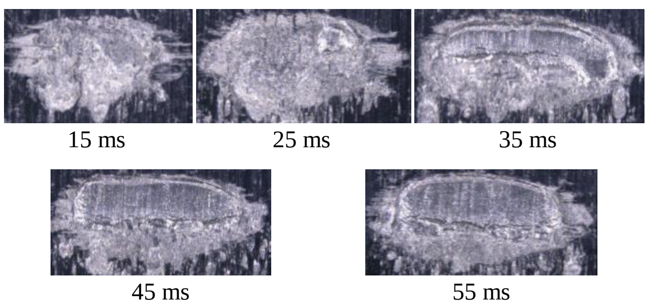

Fig. 8: Shear test residue samples of bonds produced with parameter set 2 and varied bonding time, with the tool at 430 °C

When bonding with the same parameters, vertical wire deformation as recorded by the bonding machine is higher when the bonding tool is at 430 °C than when it is at room temperature, with the mean final deformation reaching 164 µm, respectively 146 µm. This is explained by the additional heat energy brought into the process and the higher ductility and plasticity of the wire at increased temperatures, which facilitates deformation. The general course of the vertical deformation is similar in both cases, so is the variation, cp. Fig. 9.

The bond feet produced at 430 °C, cp. Fig. 10, reflect this larger vertical deformation. The imprints of the bonding tool flanks are larger, and the central area between the tool flanks is narrower than on bond feet produced at room temperature. Bond feet produced at 430 °C also are slightly (about 1 %) narrower, their edges and tool flank imprints are smoother than at room temperature. The observed differences between bond feet produced at different temperatures are similar to the differences observed by Schemmel et al. [9] between bonds produced at room temperature using different ultrasound frequencies.

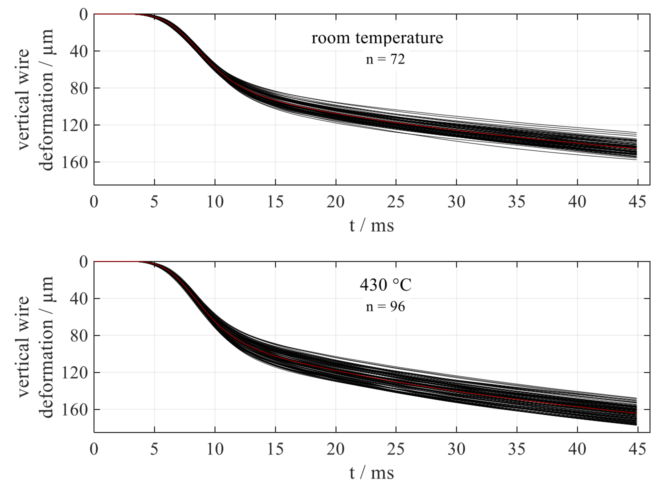

Fig. 9: Vertical wire deformation curves of bonds produced with parameter set 2, with the bonding tool at room temperature and at 430 °C; red line describes the mean curve.

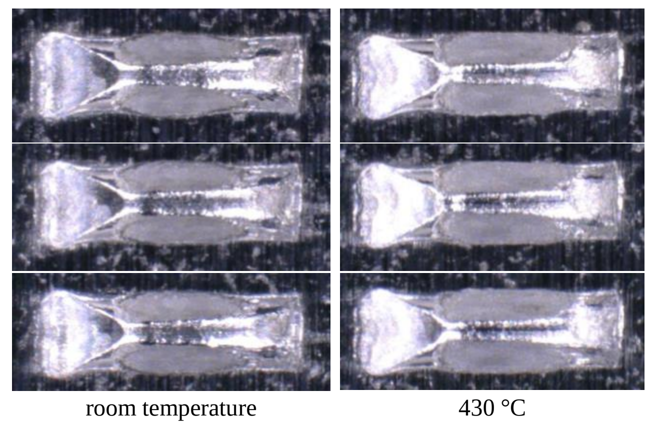

Fig. 10: Al bond feet samples produced with parameter set 2, with the bonding tool at room temperature (left) and at 430 °C (right)

B. *Copper wire*

500 µm copper wire (Heraeus PowerCu Soft) single bonds were placed on copper sheets sized 175 x 125 x 0.8 mm³ using a parameter set typical for bonding at room temperature, which is visualized in Fig. 11. Both normal force and ultrasound are much higher than in parameter sets 1 and 2 used for aluminium wire.

The results of a variation of ultrasound voltage documented in Fig. 12 show that, as in the previous test with aluminium wire, heating the tool to 400 °C increases the shear force in all investigated cases. It also allows to reach the same shear force in a shorter time or with less ultrasound. A further increase of the tool temperature to 600 °C results in a further, yet small increase of the mean shear force in all cases.

Thermal energy can also be used to substitute normal force, as Fig. 13 shows. Up to 20 % less normal force is required to obtain the same shear strength if the tool is heated to 600 °C.

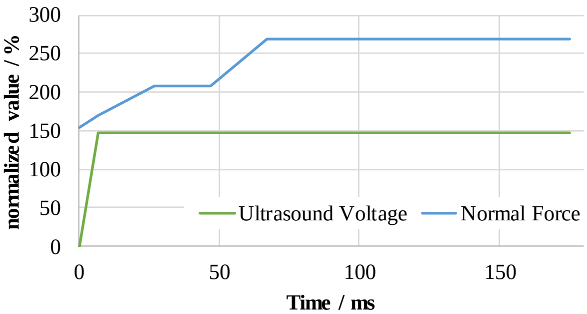

Fig. 11: Course of normalized ultrasound voltage amplitude and normal force in parameter set 3 (same normalization as Fig. 2 and Fig. 5.)

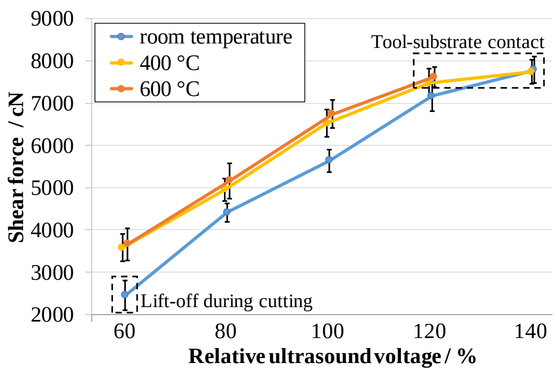

Fig. 12: Mean shear force of Cu bonds made with parameter set 3 and varied ultrasound voltage, with the bonding tool at room temperature, 400 °C, and 600 °C; error bars indicate standard deviation.

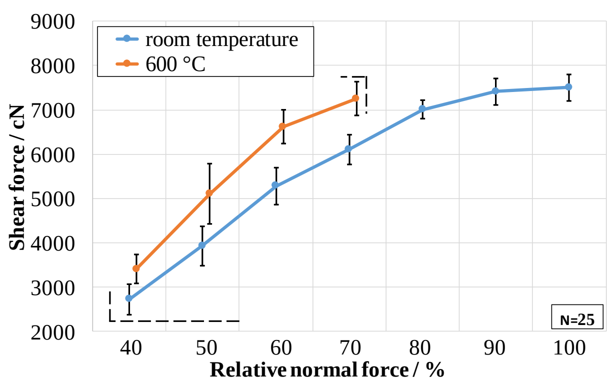

Fig. 13: Mean shear force of Cu bonds made with parameter set 3 with ultrasound voltage increased to 120 % and varied normal force, with the bonding tool at room temperature and 600 °C; error bars indicate standard deviation.

V. Conclusion

The bond test results presented above prove that thermosonic wedge-wedge bonding with a laser-heated tool has a number of significant advantages in both aluminium and copper wire bonding. It can be used to reduce the process time, to decrease the mechanical stress in the substrate by reducing ultrasound vibration amplitude and/or normal force, and to increase bond shear strength. These advantages are the same as in classic thermosonic wire bonding, but without the major disadvantage of having to heat to whole package.

A test with copper wire has shown that above a certain tool temperature, further temperature increase only has a small effect. This temperature may be material- and substrate-specific and is an object of further investigations.

The presented bond tests were made on large and thick sheets of aluminium and copper. Such sheets conduct heat away from the process zone very quickly and have a large heat capacity. Thus, the temperature difference between the tool tip and the process zone is relatively large during the bonding process. On real-world substrates such as power semi-conductors, heat drain from the process zone will be much lower and, consequently, the effects of thermosonic bonding with a laser-heated tool will be much stronger. Bonding on such substrates is another object of further investigations.

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