Submitted for publication in the proceedings of EMPC – 22nd Microelectronics and
Packaging Conference, Pisa, Italy, September 16-19, 2019

Thermosonic wedge-wedge bonding using dosed tool heating

Andreas Unger, Matthias Hunstig, Michael Brökelmann, and Hans J. Hesse

Hesse GmbH, Lise-Meitner-Str. 5, 33104 Paderborn, Germany

+49 5251 1560-681, andreas.unger@hesse-mechatronics.com

Abstract

This paper presents a novel thermosonic heavy wire and ribbon bonding process using a laser-heated bonding tool. The proposed thermosonic bonding process uses ultrasonic and thermal energy in a user-definable composition to achieve optimal connections. Through the substitution of vibration energy by thermal energy, ultrasonic vibration amplitude and/or normal force can be reduced, thus lowering the stress to the substrate. This improvement is most significant on substrates which react sensitively during purely ultrasonic bonding like battery caps, copper alloys, coated caps/clips or which are fragile like dies or sensors. Alternatively, the additional power can be used to reduce bonding time and therefore increase throughput and efficiency, or to produce stronger connections within the same bonding time. The temperature distribution at and around the bonding interface is investigated. During the process, it is necessary to ensure appropriate absorption of laser radiation at the tool tip. For this reason, a special tool with integrated optical fibre and optimized laser absorption was developed. Using a pyrometer and a closed-loop controller, the tool tip temperature is precisely controlled in real time. The temperature effect on bond strength is investigated; at a given bond duration and ultrasonic power, tool heating always increased bond strength significantly. Alternatively, the process time required for a desired bond strength could be reduced. Dosed tool heating using laser power is thus a very promising advancement in wedge bonding.

Key words: thermosonic bonding, heavy wire bonding, tool heating, laser heating

Introduction

Ultrasonic wedge-wedge heavy wire bonding is a well-established industrial process for connections in power electronics [1, pp. 33-38]. It is also increasingly used in other applications such as cell connections in automotive battery packs [2, 3].

Ultrasonic wire bonding is a “cold” process; instead of melting, the metals are bonded by interdiffusion and formation of intermetallic compounds induced by the ultrasonic vibration [1, p. 24]. As such, the process was originally done at room temperature.

Today, the vast majority of wedge-wedge wire bonds using Al or Cu wire are produced at room temperature. For thin Au 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 Cu wire ball-wedge bonding [4], is known as thermosonic wire bonding because it uses both thermal and ultrasonic energy.

Effects of Heat in Thermosonic Wire Bonding

The main motivation for thermosonic bonding is to provide some of the activation energy required to initiate interdiffusion of the bonding materials in the form of thermal energy instead of kinetic ultrasonic vibration energy [1, pp. 33-36]. In some Au 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 potentially reduce the required process time.
- Increasing temperature reduces wire material strength and reduces or eliminates strain hardening [5]. 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 a 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 [6]. 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 [7, 8], but

also ball bonds on thin microelectronic structures [9].

- Some material combinations, such as the aforementioned Au on Au, or Al on Ag [1, p. 37], can only be reliably bonded at increased temperatures.

Conventional Heating in Wire Bonding

Despite these potential advantages, thermosonic bonding is rarely used besides ball-wedge and Au wedge-wedge applications, mostly due to the limitations of available heating technology.

In current applications, heat is usually supplied through the workholder which clamps the package containing the substrate to be bonded [1, p. 6] Even if a pre-heating station is used, it takes a certain time before the substrate has reached its target temperature and the bonding process can begin. The whole package is heated, thus it must be designed to withstand the increased temperature regarding material limits and thermomechanical stress. In many applications, such as battery packs, this is not possible. It may additionally be necessary to prevent oxidation using an inert gas atmosphere around the process as it is done in Cu ball-wedge bonding [4].

Oxidation and thermal stress to the package can be avoided by not heating the whole package, but only the process zone.

In one of the first descriptions of a thermosonic process, Coucoulas [5] resistively heated the bonding tool using a special laboratory setup to obtain tool temperatures above 400 °C for bonding Al and Cu wires to thin films. While the experiments were successful, such a setup never appeared in commercial machines, probably due to the rather bulky setup and the inefficient heating system. A more compact bonding tool with integrated resistive heating has been proposed by Cho [10]. There are some commercial solutions for heating bonding tools by thermal radiation [11] and bonding tools of suitable material could also be heated by induction. In any case, at least a major part of the bonding tool is heated due to the necessary extent of the required parts and the good thermal conductivity of typical wedge bonding tool materials. For the same reason, heating takes some time and the maximum temperature is limited, as the ultrasound transducer must not exceed its maximum operation temperature.

Laser Heating in Wire Bonding

In ideal thermosonic bonding, only the process area is heated and only as much energy is supplied as is required to keep bond pad and wire at the required temperature level during the bonding process. The ideal heat source for such a process delivers high power directly to the process zone.

If the heating power is too low, parts must be heated well before the actual bonding process, using their heat capacity and thermal conduction to provide the required heating power to the process. If the heating acts far from the process zone, one must rely on long distance thermal conduction to heat the process zone. Both cases result in a lot of wasted energy and undesired heating of parts that shall remain cool, such as the ultrasound transducer.

Lasers can provide high power to a small area and thus are a promising energy source for thermosonic bonding. Some researchers have therefore investigated laser heated wire bonding in the past:

Savu et al. [12] bonded heavy Au wire on Cu substrate, heating the wire with a near infrared (IR-A) laser before and during ultrasound vibration. They did not investigate the resulting bond strength. Liu et al. [13] use an IR-A (808 nm) laser to heat bond pads on a MEMS locally and only shortly before they are contacted by the Au wire ball. Schneider et al. [14] use an IR-A (1080 nm) laser to heat heavy Cu wire before applying ultrasonic vibration to bond the wire to Cu plates. Both teams of researchers observe an increase in bond strength with increased laser power.

However, such processes suffer from the high reflectance of typical bond pad and wire materials such as Ag, Al, Au, Cu. Only a small percentage of infrared laser energy, typically less than 5 % [15], is converted into heat in the process zone. The rest is reflected in an uncontrolled way, causing undesired heating of other parts and posing a potential hazard. The laser power must be much higher than the heat flow required by the process.

Uncontrolled laser reflection into the environment can be greatly reduced, albeit not completely avoided, by guiding the laser beam inside the bonding tool, for example using a fibre as shown in Figure 1, and only activating the laser when the bonding tool touches the wire. But this does not solve the issue of low absorption, most laser energy is still reflected back into the tool or optical fibre, possible damaging the fibre or laser. For the abovementioned disadvantages, no laser heating process is yet available in a commercial wire bonding machine.

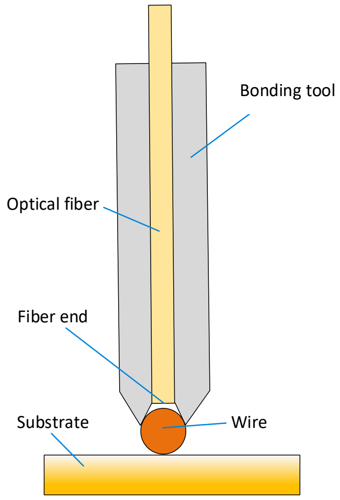


Figure 1: Schematic bonding tool design for direct wire heating with open tip

Novel Laser Heated Tool Approach

To overcome the already mentioned problems of low absorption rate of common lasers on standard wire and substrate materials, a bonding tool with integrated optical fibre and optimized laser absorption for indirect wire heating was developed. The laser radiation is used to heat the tool tip during or immediately before the bonding process to heat wire and interface by thermal conduction and thus enable a thermosonic bond process. This tool offers significant advantages compared to a tool with open tip as shown in Figure 1. Previous studies have shown that standard bonding tool material (tungsten carbide in cobalt matrix) has an absorption rate of approximately 70 % at IR-A wavelengths, much more than the less than 5 % of standard wire materials [15]. This dramatically increases the share of the laser power usable in the process, enabling the use of laser sources of relatively low power.

Mechanical and thermal long-time tests with various tool variants were carried out. The operating principle and the developed bonding tool are shown in Figure 2. central hole in the tool is used to place the end of the fibre centrally inside the tool, pointing towards the tip. The section towards the tool tip increases the effective area on which the laser beam is absorbed after leaving the fibre. This reduces the intensity of the incident radiation and the resulting local thermal stress for the tip. Another important benefit is the decreased resulting reflection to the laser system because of the beam trap character of the geometry. If energy is dissipated at the end of the fibre, the resulting heat can damage the fibre and also impairs accurate temperature measurements through the fibre as described below.

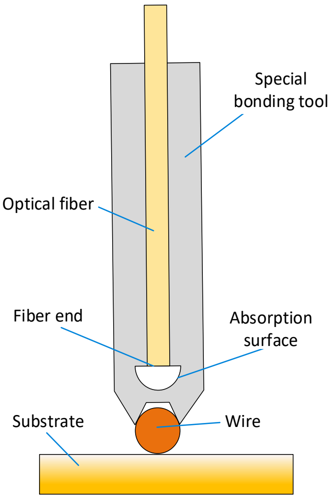


Figure 2: Schematic bonding tool design for indirect wire heating with laser absorption surface

Finite Element (FE) Heating Simulation

Based on previous investigations, the process temperature required to achieve the desired effects in bond formation (time reduction, normal force reduction, substitution of mechanical vibration power, general bondability) was expected to be 150-200 °C, which is within the typical range for conventional thermosonic processes [1, p. 36]. In order to determine the required tool temperature for heating the interface to this temperature, a 3D finite element (FE) model of the contact partners bonding tool, wire and substrate/DBC was created using ANSYS. As shown in Figure 3, the copper wire with a diameter of 500 µm is placed under a standard wire bonding tool (tungsten carbide in cobalt matrix) on a 300 µm thick copper layer of a DBC. In order to produce the (thermal) contact conditions of a normal wire bond, the wire portion under the tool was deformed to model the deformation occurring in an ultrasonic bonding process in the so-called pre-deformation phase due to the applied normal force.

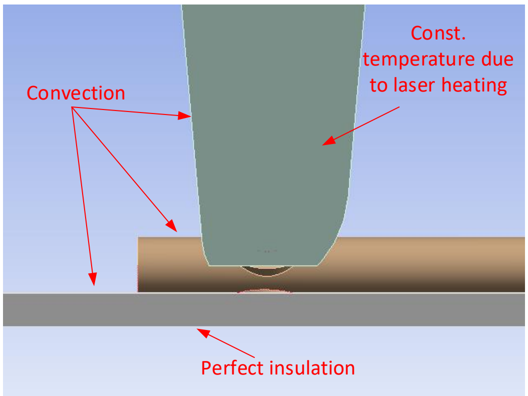


Figure 3: Finite element model for thermal analysis

The following boundary conditions were defined in the thermal simulation in order to obtain valid results: The temperature is assumed to be constant in the tool tip due to closed-loop temperature control (see paragraph ‘Tool Temperature Control’). To consider the natural convection of the cooling air, a convective load is placed on the surfaces of the tool, wire and substrate with a convection coefficient of 5 $\mathrm{W/m^2}$ and an ambient temperature of 22 °C. For the simulation, the ceramic underneath the DCB copper layer is assumed to be a perfect insulator. Wire length and substrate extent were chosen so large that their outer regions remained very close to ambient temperature.

Thermal conductivities are assumed as 400 W/(m·K) for copper and 70 W/(m·K) [16] for the tool. The simulation results are also affected by the contact settings. In ANSYS, the resistance to solid/solid thermal conduction per unit area at the interface is included as a user supplied real constant value of thermal contact conductance (*TCC*) in $\mathrm{W/m^2K}$. The relationship between *TCC*, heat flux and temperature is given by:

$$q = TCC\,(T_{\mathrm{hot}} - T_{\mathrm{cold}}) \tag{1}$$

where q is the heat flux per unit area (in $\mathrm{W/m^2}$), T_{hot} (in K) is the local temperature on the hot surface and

T_{cold} (in K) is the local temperature on the cold surface [17]. The current understanding of the Thermal Contact Conductance under ultrasonic bonding conditions is limited. Thus, the values of *TCC* are difficult to predict. For this reason, the values of *TCC* for the contact tool/wire and wire/substrate are set to $35\mathrm{x}10^6$ W/(m^{2}K) which corresponds to a thermally bonded contact of two solids. Due to the high thermal conductivity of copper and the relatively low conductivity of the tool material, the heat flow into the wire is more than twice as high as the heat flow into the upper part of the tool.

Figure 4 shows the FE-calculated temperature distribution in the interface after linearly ramping the tool temperature from 22 °C to 400 °C within 35 ms and then keeping it at this temperature for another 300 ms. The resulting temperature in the interface rises to 148 °C. The heat affected area in the substrate is very small compared to a conventional substrate heater. This approach thus enables local heat application to the interface during the bonding process without affecting the surrounding material very much.

In addition, simulations were performed for different tool temperatures between 100 °C and 500 °C to evaluate the effect of the tool temperature on the resulting interface temperature. The results can be seen in Figure 5. As expected, the interface temperature shows a typical bounded growth course. A steady interface temperature is not achievable for typical bond times. This can be explained by the high thermal conductivity of copper and the high thermal flux into DBC and wire.

A stationary analysis was also performed to calculate the temperature gradient in the bonding tool and the transducer. The result is presented in Figure 6. It shows that heat conduction from the heated tool tip only slightly increases the transducer temperature. Thus, heating-induced temperature effects on the transducer are very limited. This is especially important to ensure a stable bonding process over time.

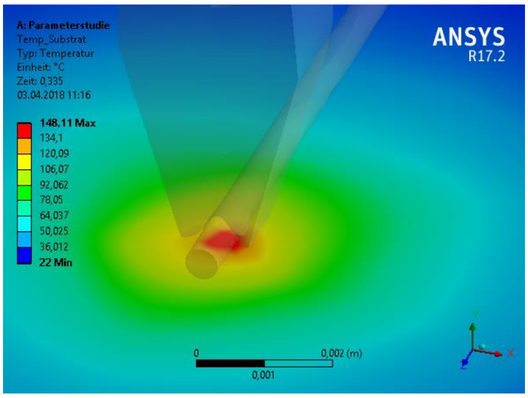


Figure 4: Transient temperature distribution in the interface of wire and DCB, snapshot for 400 °C tool temperature after 335 ms

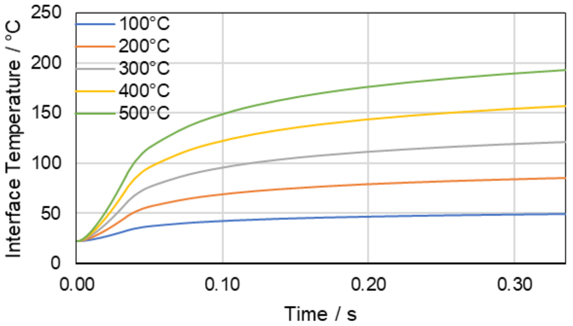


Figure 5: Temperature course in the bonding interface for different tool temperatures (22 °C before 0 s, specified temperature from 35 ms, linear ramp in between)

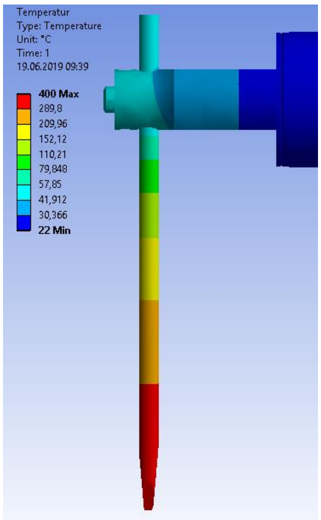


Figure 6: Steady state temperature distribution within bonding tool (slim rod) and transducer tip for a constant tool tip temperature of 400 °C

Tool Temperature Control

To provide the required energy in the real thermosonic process, a near infrared laser source has been integrated into the wire bonding setup via an optical fibre, cp. Figure 7. The temperature is controlled by pyrometry, with the pyrometer projected coaxially into the laser beam by a beam splitter to combine temperature measurement and laser heating in one optical fibre. This fibre ends in a heavy wire bonding tool for copper wires with 500 µm diameter. The pyrometer is connected to an external controller to measure and control the tool tip temperature simultaneously. Controlling the temperature ensures a consistent quality of bond connections. A Hesse Mechatronics Bondjet BJ959 automatic bonding machine equipped with a standard wire bondhead is used for bonding tests on rolled copper plates.

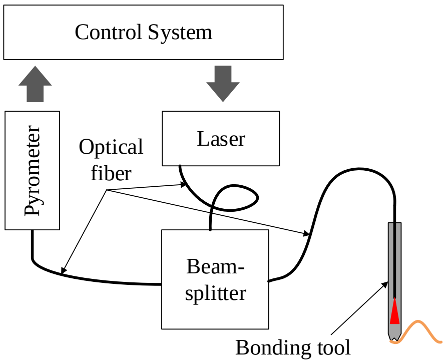


Figure 7: Schematic of the optical design for implementing a process control

For validation of the temperature control, a target temperature profile was defined for the tool without contact and without wire which started at 22 °C, jumped to 500 °C for 14 seconds, and returned to 22 °C. The resulting temperature of the tool tip measured using the pyrometer and simultaneously using a thermal camera. As the results presented in Figure 8 shown, the set target temperature is reached quickly and accurately. At the beginning, rapid warm-up is required, thus the controller quickly increases the laser power, cp. Figure 9. After reaching the target temperature, the laser power required to hold this temperature decreases significantly over time, as less heat is conducted into the already heated rest of system. Once the target temperature drops, the laser is switched off and the temperature slowly falls towards the 22 °C target, as there is no active cooling system. As a reference also shown in Figure 8, the temperature was measured with a thermal camera. Using similar emission coefficients, the data from pyrometer and thermal camera show good agreement.

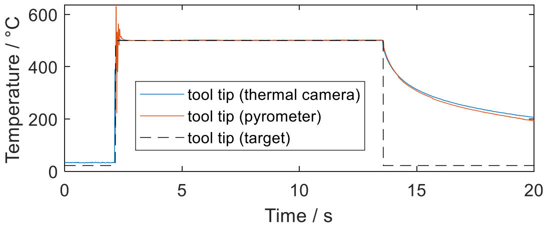


Figure 8: Set and measured temperature during temperature control experiment (free tool tip)

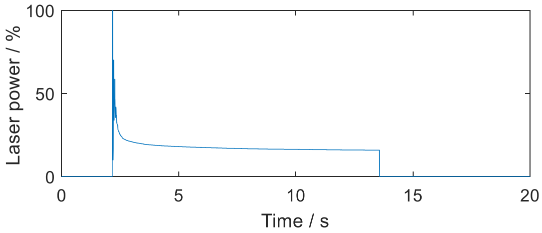


Figure 9: Laser power, set by temperate controller, during temperature control experiment (free tool tip)

Figure 10 shows the results of a similar investigation during a bonding process. Each plateau indicates a bonding phase using a constant tool temperature of 450 °C, ultrasound is applied for 335 ms. Between the heating phases, when the tool moves to the next bond location, the temperature drops to an undefined value. As the next bond starts, the temperature quickly rises to 450 °C again. Figure 11 shows a side view of all relevant components during this process, observed using a thermal camera. The results confirm that the high power of the laser directly and quickly heats up the tool tip which then heats wire and substrate.

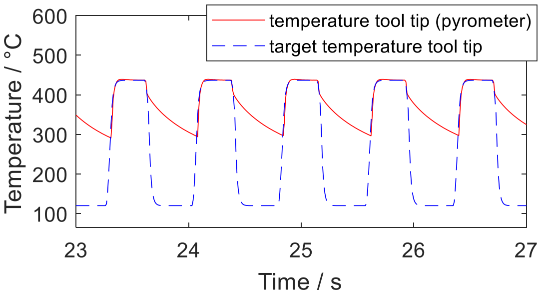


Figure 10: Resulting temperature plateaus during the wire bonding process

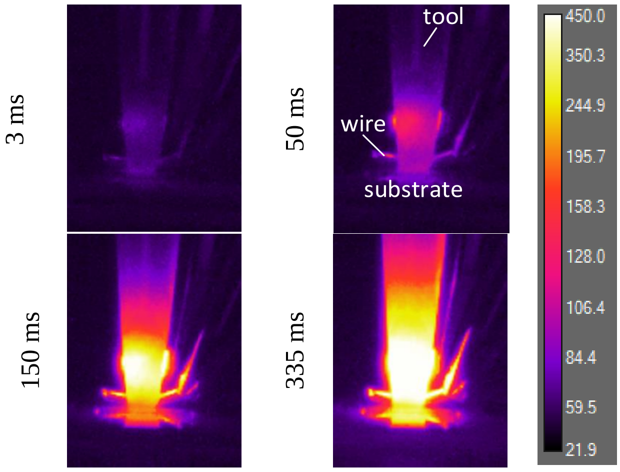


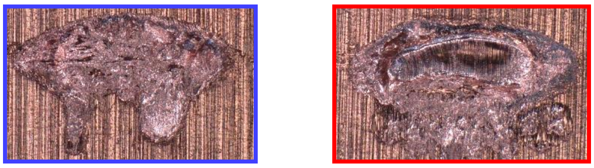
Figure 11: Temporal development of a tool heating process during a source bond (thermal camera images)

Wire Bonding Results with Tool Heating

For evaluation purposes, the mechanical strengths of 500 µm copper wire bonds created using the novel thermosonic process are investigated. Bonding tests showed a very positive influence of the added thermal energy. Figure 12 shows this clearly. The target shear force is approximately 6000 cN. The ultrasonic transducer voltage U_S required to achieve this bond strength in a “cold” ultrasonic process is defined as U_{S0} = 100 %. At U_S = 50 %, no bond connections were observed. However, if the tool tip is heated to a temperature of 450 °C, a shear force of about 4000 cN is reached already at this low voltage.

With such a heated tool, the target strength is already reached at $U_S = 70\ \%$, doubling the shear force of 3000 cN obtained in the corresponding cold process. At higher ultrasonic power, the gain is naturally reduced, still is approx. 33 % at $U_S = 100\ \%$, where the thermosonic process produces a shear force of 8000 cN. The associated bonds show excellent properties with a full-surface intimate welding, so that the shear test tool sheared through the wire material and the joining zone remained intact (‘nugget’, Figure 12, top right).

Further tests have proven that instead of reducing ultrasonic vibration power, heating the tool can also be used to reduce the process time while maintaining the same desired bond strength.



T=22°C (without Laser) T= 450°C (with laser)

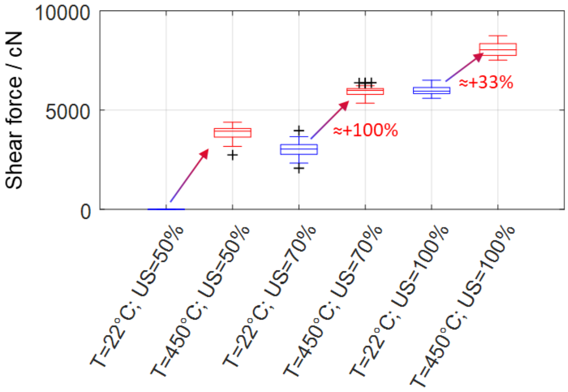


Figure 12: Shear strength of source bonds (500 µm Cu) produced using different ultrasonic voltage U_S and tool tip temperature T

Conclusions and Outlook

Thermosonic bonding, combining ultrasonic and thermal energy to form a bond, has several advantages over cold ultrasonic bonding. But it can currently only be used industrially by heating the whole package through the workholder, which excludes many otherwise promising uses. Lasers can provide high power to a small area and thus are very promising for the use in thermosonic bonding with focused local and temporal heating. The low absorption rate of most bonding materials is a critical drawback for direct laser heating of the bond. This drawback is overcome by heating the tool tip instead, which provides very high and constant thermal energy dissipation thanks to its high absorption (material property) and the special design of the absorption structure (geometry and surface).

In the presented setup, a bonding tool with integrated fibre was used. The fibre provides laser energy to the tool tip and is concurrently used for temperature measurement by pyrometry. The tool tip can be heated up to 500 °C, target temperatures up to this limit are reached precisely by a closed-loop laser power controller. Using a FE model, the effect of a heated tool tip on surrounding materials was analysed. The results show that the temperature of the local interface reaches the desired 150-200 °C in a very short time. This was validated using a high-speed thermal camera.

Investigation of the temperature effect on bond strength shows a significant benefit of laser assisted thermosonic bonding over conventional ultrasonic bonding. At a given bond duration and low ultrasonic power, bonds of significant strength could be formed using the thermosonic process, while no bond formed in the cold process. At larger ultrasonic power, the bond strength increased significantly compared to the cold process.

Thermosonic wedge-wedge bonding using a laser-heated bonding tool is thus a very promising advancement for enabling wire bonding applications on sensitive substrates requiring low normal force or low ultrasonic vibration as well as for reducing process time in any wire bonding process. While not investigated in this contribution, it is also expected to enable connections not feasible in a cold ultrasonic process or increase bondability like in gold bonding.

Further investigations with aluminium and copper wire will be performed in the future to verify the results for industrial applications like semiconductor modules with dies and for challenging processes like battery bonding. Additionally, deep parameter studies will be conducted, e. g. with shorter process times, as well as extensive endurance tests.

Acknowledgements

The contents of this paper are results of the joint research and development project “InnoWeBo”, conducted in cooperation with CeramOptec GmbH and Laser Zentrum Hannover e. V. and funded in the framework of “Zentrales Innovationsprogramm Mittelstand” (ZIM) by the German Federal Ministry for Economic Affairs and Energy due to a resolution of the German Bundestag.

References

[1] G. Harman, “Wire Bonding in Microelectronics”, 3rd ed., McGraw-Hill, New York, 2010
[2] C. Ruoff, “A closer look at wire bonding”, Charged – Electric Vehicles Magazine, No. 24, pp. 18-27, Mar/Apr, 2016, https://chargedevs.com/features/a-closer-look-at-wire-bonding/
[3] A. Das, D. Li, D. Williams, D. Greenwood, “Joining Technologies for Automotive Battery Systems Manufacturing”. World Electr. Veh. J., Vol. 9, 22, July, 2018
[4] Z. W. Zhong, “Wire bonding using copper wire”, Microelectronics International 26 (1), pp. 10-16, 2009

[5] A. Coucoulas, “Hot Work Ultrasonic Bonding - A Method of Facilitating Metal Flow By Restoration Processes” Proc. 20 IEEE Electronic Components Conf., pp. 549-556, 1970.
[6] B. Langenecker, “Effects of Ultrasound on Deformation Characteristics of Metals”, IEEE Trans. Son. Ultrason. 13 (1), pp. 1-8, 1966
[7] K. Guth, D. Siepe, J. Görlich, H. Torwesten, R. Roth, F. Hille, F. Umbach, “New assembly and interconnects beyond sintering methods”, Proc. PCIM, pp. 232-237, Nürnberg, Germany, 2010.
[8] J. Rudzki, F. Osterwald, M. Becker, R. Eisele, M. Poech, “Power Modules with Increased Power Density and Reliability Using Cu Wire Bonds on Sintered Metal Buffer Layers”, 8th Int. Conf. Integrated Power Electronics Systems (CIPS), pp. 451-455, Nürnberg, Germany, 2014
[9] G. Singh, A. S. M. A. Haseeb, “Effect of Pedestal Temperature on Bonding Strength and Deformation Characteristics for 5N Copper Wire Bonding”, Journal of Electronic Materials, 2016
[10] J. W. Cho, “Wire bonding wedge tool with electric heater”, Patent US 5 958 270, 1999.
[11] DeWeyl Tool Company, “Heated Capillary Holder”, https://www.deweyl.com/assets/pdfs/heater_tools.pdf, accessed 2019-06-05
[12] Savu, I. D.; Savu, S. V.; Sebes, G.: “Preheating and heat addition by LASER beam in hybrid LASER-ultrasonic welding”, J Therm Anal Calorim Vol. 111, pp. 1221–1226, 2013
[13] Liu, Y; Sun, L.: “Laser-heating wire bonding on MEMS packaging”, AIP Advances, Vol. 4, Issue 3, ID 031312, 2014
[14] F. Schneider, Y. Long, H. Ohrdes, J. Twiefel, M. Brökelmann, M. Hunstig, A. Venkatesh, J. Hermsdorf, S. Kaierle, L. Overmeyer, “Effect of laser assistance in ultrasonic copper wire bonding”, Lasers in Manufacturing Conference, Munich, Germany, June 26-29, 2017
[15] U. Dürr: “Reproduzierbares Laserschweißen von Kupferwerkstoffen“, Metall – Fachzeitschrift für Metallurgie, Vol. 62, No. 10, pp. 647-650, 2008 (in German)
[16] Goodfellow, “Tungsten Carbide/Cobalt (WC 94/Co 6) Material Information”, http://www.goodfellow.com/E/Tungsten-Carbide-Cobalt-Ceramic.html, accessed 2018-08-08
[17] M. K. Thompson, J. Thompson, “Considerations for Predicting Thermal Contact Resistance in ANSYS”, Proceedings of the 17th Korea ANSYS User's Conference, 2007