

Next generation of Thermo-Compression Bonding Equipment

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Abstract

As transistor technology node scaling slows down, alternative approaches are being explored to sustain the momentum of Moore's law. Chip sizes have now reached reticle limits, posing challenges for adding more features. Additionally, large dies come with their own set of disadvantages, including reduced yield, longer time to market, increased complexity, higher design and engineering costs, limited flexibility for customization, and an inability to utilize different nodes for various architectures to reduce costs. While material selection is a critical aspect which can help, packaging has more prominently taken the spotlight. A state-of-the-art thermocompression bonding (TCB) equipment has been proven to achieve sub micron accuracy, and implementation of a no flux TCB process with hydroxyl reduction proven via cross sectioning of specimens. Innovative ways to deal with search inaccuracies performed by cameras induced from elevated temperatures are also presented with nm repeatability.

Introduction

Heterogeneous integration is emerging as a key enabler for advanced packaging, allowing a single System on Chip (SoC) to be divided into multiple smaller dies or chiplets, which helps reduce complexity, costs and time to market. This approach requires different chiplets from various nodes and interconnect technologies to coexist within one package. However, the complexity of this integration can lead to significant issues if process flow and material selection are not carefully planned. Traditional interconnection methods like flip-chip bonding, which involves mass reflow, can adversely affect sensitive components and compromise package stability, including the risk of warpage. With high-end packaging projected to gain market share in the coming years (Figure 1), TCB offers a promising solution to these challenges. The Heterogenous integration roadmap (HIR) (Figure 2) identifies TCB as an enabling interconnect technology that supports advanced packaging schemes at all three die levels, including 2D & 2D Enhanced, 2D Enhanced with 3D Die-to-Die and Die-to-Wafer, and full 3D Die-to-Die and Die-to-Wafer configurations.

TCB fundamentals

Thermo-compression bonding (TCB) emerged as a solution for finer pitch applications. TCB uses wafers equipped with copper (Cu) pillars and solder caps, limiting the amount of solder to allow for closer spacing between Cu pillars and higher interconnect density. There are various types of TCB, but the primary approach involves local solder reflow while holding the die and substrate in place, followed by cooling to solidify the solder and secure the die to the substrate. The die is typically released only after the solder has partially or fully solidified. This method achieves higher

precision, as it doesn't depend on the self-centering effect of solder, and also mitigates warpage issues by keeping both the die and substrate flat during bonding. Additionally, TCB allows active control over bondline thickness (BLT), ensuring a uniform solder shape for interconnects and facilitating subsequent processes like underfill.

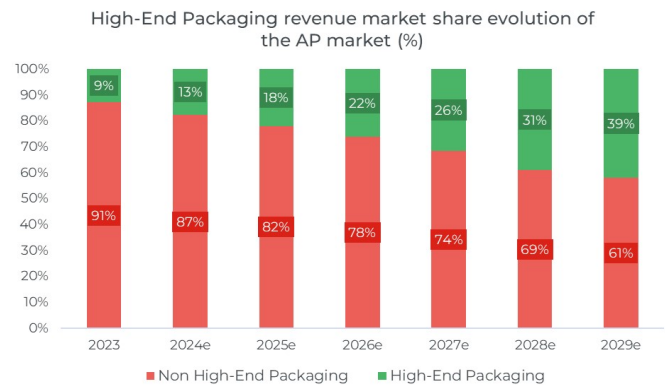


Figure 1. High-end packaging revenue market share evolution [1].

Architecture Type (2D / 2D Enhanced / 3D)	Interconnect Technologies	Tightest Die to Package Pitch ²⁷	Typical Interconnection Process	Typical Equipment
2D [44]	Wire-Bonding	25 μ m	Wire-bonding	Wire-Bonder
2D & 2D Enhanced [45]	Micro-bumps, C4s, TSVs, and passive Si Interposer	20 μ m	- Thermal compression bonding (TCB) - Mass reflow	Thermo-compression bonding (TCB) tools, Reflow oven
2D Enhanced, 3D die-to-die, die-to-wafer [46-48]	Cu pillars, passive and active Si coupons & wafers	< 10 μ m	- Solderless Cu-Cu thermal compression bonding (TCB) - Mass-reflow	Modified Thermal compression bonding (TCB) tools
3D Die-to-Die, Die-to-Wafer [49-58]	Micro-bumps, TSVs, Cu-Cu Bonding	5 μ m	- F2F or F2B Direct Cu-Cu bonding interconnection - Thermal compression bonding with Cu-Solder interconnection	Custom bonding equipment
3D Wafer-to-Wafer [50]	Cu-Cu Bonding	0.9 μ m	F2F or F2B Direct Cu-Cu bonding interconnection	Custom bonding equipment

Figure 2. Excerpt from HIR for Interconnects for 2D and 3D Architectures [2].

In the TCB process, a fluxing agent is required, which can be applied in either liquid form or as a film. Unlike in mass reflow flip chip, the flux does not need to be highly tacky to prevent die shift caused by movements in the bonder, conveyor system, or oven. Instead, the flux's role is to use the right chemical composition and heat cycle to reduce surface oxides. The combination of appropriate chemistry and processing helps ensure a clean, oxide-free, solder-wettable metal surface, which is essential for achieving strong metallurgical bonding. Additionally, the flux aids in oxide reduction and acts as a medium for heat transfer.

The four main types of TCB are TCB with Capillary Underfill (TC-CUF), TCB with Molding Underfill (TC-MUF), TCB with Non-Conducting Paste (TC-NCP), and TCB with Non-Conducting Film (TC-NCF), as illustrated in Figure 3. In TC-CUF, the process involves picking up a die, dipping it in flux (or using pre-applied flux on the substrate to skip this step), moving it to the bond position, making contact with bond pads on the substrate or substrate wafer, applying force and heat, cooling, cleaning off the flux, and applying underfill. However, the need to minimize the Keep Out Zone during underfilling, driven by narrower die-to-die spacing and ultra-thin dies (50 μm or less), poses a significant technical challenge for TC-CUF. As pitch sizes shrink, pillars get smaller, and dies grow larger, effectively cleaning flux residues between the die and substrate becomes increasingly difficult, making this process less favorable.

As a result, TC-MUF was developed as an alternative encapsulation method for flip chip applications. TC-MUF follows the same process as TC-CUF, but instead of applying underfill, the module is encapsulated through molding. This approach became viable due to advancements in molding compounds, which enabled better penetration into the narrow gaps between the die's underside and the substrate, as well as between the Cu pillars.

TC-NCP involves dispensing a non-conductive paste onto the substrate, allowing the die to be bonded directly without the need for flux dipping. Once cured, the NCP hardens, eliminating the need for underfill. However, as thin die handling becomes more common, challenges arise, including the risk of NCP creeping onto the top die surface. Another issue is the prolonged exposure of NCP to substrate heating, which can alter its properties, particularly in wafer-level applications with a higher number of bond modules. This concern also applies to die stacking. Additional challenges include void formation and the reliability of solder connections. The trend toward narrower gaps, finer pitches, and higher bump counts makes it difficult to properly fill the space, often leading to voids in the NCP. Since TCB occurs after pre-dispensing, there is a risk of filler material becoming trapped between the solder and Cu bump, which can eventually result in solder bump connection failures. To address these challenges, the industry transitioned to a film-based version of NCP, known as NCF.

TC-NCF uses a pre-applied film, typically placed on the underside of the component wafer before singulation, eliminating the need for flux dipping. The die is bonded, and careful selection of process parameters is required to ensure proper bonding. NCF material consists mainly of epoxy, a flux agent, curing agent, and fillers, making it difficult to

distinguish from epoxy flux, NCP, or no-flow underfill. This means that no separate flux application is needed. TC-NCF offers several advantages, such as addressing the time-on-stage concerns present in TC-NCP, as the NCF material is laminated onto the bonded die rather than the substrate wafer. It also prevents underfill overflow on thin dies, which could otherwise damage the bondhead. Additionally, TC-NCF is the preferred method for 3D stacking applications, as it accommodates multiple solder reflow cycles. Without encapsulation, applying force and heat to bond a second die risks over-compressing the first die against the substrate.

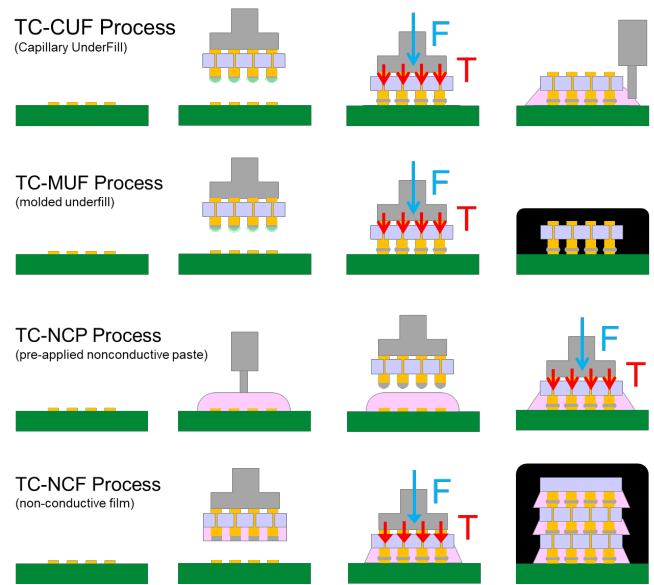


Figure 3. Types of TCB processes.

Despite its advantages, TC-NCF also presents challenges, particularly in preventing void formation during film application. Voids may already exist within the film or form due to improper TCB process parameters, potentially disrupting the connection between the Cu pillar and bond pad, leading to an open circuit. During outgassing, these voids can serve as nucleation points, allowing them to grow larger and cause significant quality issues, such as the risk of electromigration. This occurs when the NCF bridges gaps between closely spaced wires, pads, and bumps, all of which have different electrical potentials.

With the challenges posed by TC-NCF, the industry is now exploring a new TCB method for fine-pitch applications, typically in the 10 μm to 25 μm range, known as fluxless TCB. As the name suggests, this approach eliminates the use of flux in any form. In fluxless TCB, the die with Cu pillars and solder caps is bonded directly to the substrate without any intermediary medium. However, oxidation removal becomes a critical issue, as oxidation inhibits solder wettability and the formation of a metallurgical bond with the base material. The process must ensure that any existing oxidation is removed before die-to-substrate contact and prevent new oxide formation as temperatures increase during the TCB process.

No-flux TCB

The key requirements of a fluxless TCB process are tabulated in Table 1.

Table 1. No Flux TCB key requirements.

Active oxide reduction	Targeted and efficient process suitable for a wide range of common materials
Contamination-free	Foreign substances affect reliability and higher wettability
Quality and Compatibility	Compatible with Chip to Substrate (C2S) and Chip to Wafer (C2W) processes (no damage on PCB or silicon surfaces)
High throughput	Needs to ensure attractive total cost of ownership (TCO)
Safety	Non-toxic chemical agents, if any and easy chemical handling
Cost of ownership	Module & consumable pricing must be reasonable and must ensure efficient use of commonly available agents
Surface protection	Inert atmosphere transfer and bonding as well as exploitation of passivation effects

When screening for technologies suitable for fluxless bonding, several boundary conditions must be met to ensure compatibility with die-to-wafer or die-to-substrate processes:

- **No Re-Oxidation:** Re-oxidation must be completely avoided in the bonding equipment. Maintaining an inert atmosphere with low oxygen content is essential.
- **Effective Treatment Methods:** Techniques from the front-end process require enclosed chambers with wet or vacuum treatments. These methods are most effective when treating at least one wafer at a time, as throughput can be compromised otherwise.
- **Short Processing Time:** Ideally, the material should be processed in a low-oxygen environment and as close to the actual bonding zone as possible to minimize existing oxide layers.
- **Mitigation of Side Effects:** Unintended side effects, such as surface damage (etching), residue left after treatment, or electrostatic discharge (ESD) concerns due to high voltage electrodes near the material, must be managed effectively.

Among the various candidates for fluxless bonding processes (see

Table 2), two options particularly stand out for their compatibility with fluxless bonding equipment operating at temperatures suitable for TCB: gaseous light carboxylic acids, such as formic acid, and certain hydrogen-based treatments.

Table 2. No-Flux TCB technology screening

	Passivation	Wet etching	Dry etch/ Sputtering	Carboxylic acids	Hydrogen-based
Reduction	No (only protection)	Well established			
Passivation	Yes	No			Some reported
Lot treatment vs continuous	Lot only (Wet chamber)		Lot (Vacuum)	Both	Both (with certain systems)
Reduction rate at < 150 °C	n/a	High	Low	Low	Medium
Reduction rate at < 250 °C	n/a	High	Medium	High	
Residue mitigation	Film requires wash, pyrolysis	DI wash	(few) Particles	Organic residue, whisker risk	None required, (few particles)

Figure 4 provides a comparative analysis of the chemical reaction kinetics for various potential reducing agents. The first line of the table (red bar) displays the enthalpy of formation for the metal oxide. The reactions are evaluated based on their Gibbs free energy within a typical temperature range of 180-250°C. A blue bar indicates an energy release during the reaction, with the bar length representing the amount of energy released. All reducing agents are gases (g), and in the case of hydrogen, they may be in neutral, cationic, or anionic forms. Acetic acid (indicated by an asterisk) is included as a more complex carboxylic acid compared to formic acid (indicated by a double asterisk). A positive value (red) indicates the catalytic effect of SnO₂, used for instance in hydrogen production. The data clearly shows that formic acid and most hydrogen-containing gases (neutrals, ions, radicals) are highly effective reduction agents for tin and copper oxides (blue). However, this should not be confused with the actual reaction rates, which depend on specific implementation details such as reducing agent density or the thermal activation energy required to overcome surface barriers.

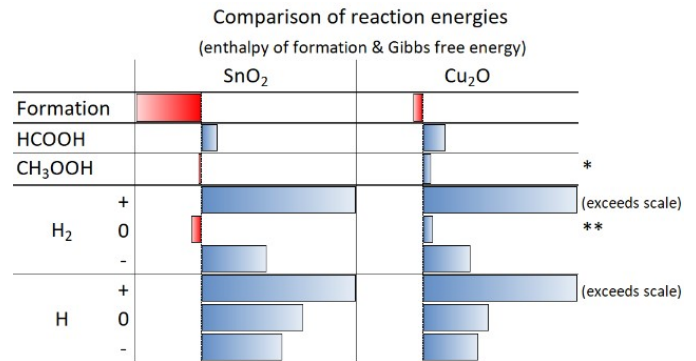
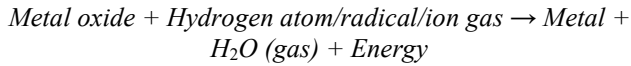


Figure 4. Relative enthalpy of formation ΔH_f for copper and tin oxides and the Gibbs free energy ΔG for the oxide reduction reaction at typical temperatures between 180-250°C. Thermochemical data from [3].

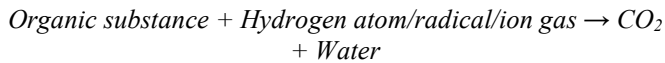
Formic acid vapor, when used, is adsorbed to form a metal formate that requires high activation temperatures, typically above ~250°C [4]. This extended exposure to high temperatures can be problematic for sensitive devices like DRAM memory. Additionally, a certain dwell time is necessary for the chemical reaction to effectively remove or reduce oxides, especially on copper, which is more resistant. This can affect throughput or necessitate extensive pretreatment [5]. Concerns also include potential carbon residues on the surface [6] and the growth of tin-formate crystal whiskers in the bonding chamber [7]. Safety is crucial for High Volume Manufacturing (HVM) applications,

requiring careful measures to exhaust hazardous gases, detect leaks, and implement safeguards to protect users.

Therefore, hydrogen-based fluxless bonding treatments shall be preferably considered. Figure 4 reveals that pure hydrogen gas is likely not the best choice for tin oxide. For safety reasons, hydrogen is best used as forming gas mixture (e.g. with Argon or Nitrogen), which additionally helps with the purpose of keeping the oxygen levels. Hydrogen reacts with the tin or cuprous oxide to produce H₂O as a byproduct, i.e.



where organic intermediate salts are completely avoided, in contrast to acidic treatment. Additionally, the hydrogen reducing agents essentially clean the surface of the material via:



Previously, it was also reported that some hydrogen-based metal oxide treatments leave a thin layer of hydrogen adsorbed on the surface [6]. This layer might serve essentially as passivation treatment that is thermally activated during TCB, serving as “no-residue flux”.

TCB equipment requirements for the ongoing and future era

As the market pushes for advanced packaging to maintain Moore’s Law, the demand for higher I/O density continues to grow, driven by applications in HPC, AI, edge computing, and data centers. TCB has demonstrated its capability in high-volume manufacturing (HVM) with pitches down to 25µm, and industry leaders are now targeting even finer pitches, down to 10µm, with advanced wafer preparation and packaging processes.

One promising approach is fluxless TCB, which eliminates the need for flux in any form—liquid, paste, or film. Success with this method depends heavily on wafer design and manufacturing, as well as innovative TCB techniques. For fluxless bonding, the bonder must maintain an inert atmosphere to prevent oxidation, which can accelerate at high temperatures and with exposure to oxygen. Ideally, this would be combined with an oxidation removal step to ensure clean surfaces on both the component side (with solder-capped Cu pillars) and the Cu pads on the substrate wafer. Alternatively, using a reducing atmosphere can actively remove and prevent oxidation.

Both approaches involve significant gas consumption, impacting the total cost of ownership (TCO). Achieving low oxygen ppm levels is crucial, but the cost and time required to reflood the chamber and reach stable oxygen levels after an intervention or product change are critical factors. Machine downtime during this process directly affects return on investment (ROI), making efficient gas management and rapid stabilization essential for maintaining cost-effectiveness.

One notable bonder, depicted in Figure 5, excels in gas consumption, achieving <100ppm oxygen levels with a remarkable rate of 75l/min, thanks to its innovative design. Unlike traditional bonders that seal off large areas and flood them with gas while maintaining standard die attach module locations, this bonder features a complete redesign. It boasts an ultra-low volume tunnel and integrates essential modules, such as the substrate camera, uplooking camera, substrate wafer, and auto bonding nozzle changer directly within the tunnel. This design minimizes variations in oxygen ppm levels, ensuring efficient and stable performance.



Figure 5. Dual TC bonder exterior (left) and interior showing inert tunnel, bondhead, auto tool change etc

The operation of this bonder, as illustrated in Figure 6, is characterized by several key features. The bondhead nozzle remains continuously inside the tunnel, capable of movement along the Z and X axes. Component dies are introduced into the tunnel via a separate module known as the die lift. The bondhead picks up the die after optional alignment and then moves to the bond position, aligning over the UC (also within the tunnel) and performing the bond after a Y-axis movement by the bonding stage. This separation of movements between the bondhead and the bonding stage enhances throughput and accuracy, while ensuring that components are consistently exposed to the controlled environment inside the tunnel, thus minimizing oxidation.

The schematic also highlights that the nozzle change occurs within the tunnel, eliminating the need to open it for product changes. This prevents contamination and preserves the integrity of the gas atmosphere, avoiding the wastage of gas and the need to reestablish <100ppm oxygen levels. Additionally, the tunnel remains sealed throughout the process, eliminating downtime associated with environmental stabilization.

Figure 6 includes a cross-sectional image of Cu pillar TCB. The top image shows a no-flux bond without oxidation reduction and without a controlled gas atmosphere, revealing poor solder fusion. In contrast, the bottom image displays a fluxless TC bond achieved with hydroxyl reduction and inert atmosphere, illustrating the effectiveness of the controlled environment.

The need for increased bump density and tighter tolerances necessitates a corresponding enhancement in placement accuracy. Modern TC bonders must achieve sub-1µm accuracy to handle 10µm pitch devices effectively. The bonder depicted in Figure 5 meets this requirement, achieving ±0.75µm@3σ and ±1.05m°@3σ with a large 30x20mm glass die, after 1800 placements across various wafer surface areas, utilizing in-situ measurements. The large die size was specifically selected to test the bonder under worst-case conditions, where large dies nearing the reticle size limit

require stringent tolerances due to significant lateral offsets from even minor rotations. This performance assures high confidence in the bonder's readiness for high-volume manufacturing (HVM) for next-generation packaging.

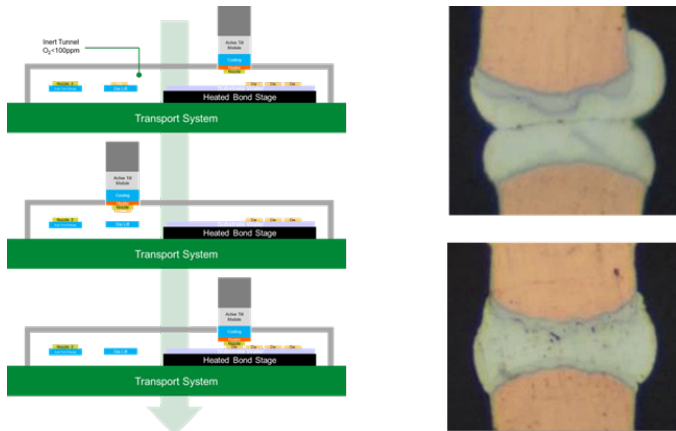


Figure 6. Mode of operation of bondhead inside tunnel (left) and cross sections (right) comparing TCB without hydroxyl reduction and inert atmosphere tunnel (top) and with hydroxyl reduction and inert atmosphere tunnel (bottom).

In addition to lateral accuracy, precise control of the z dimension is crucial in TCB to avoid issues such as solder bridging or squeeze out. The bonder achieves exceptional bond control in the nanometer range by splitting the z movements into two axes: z and w. The primary z-axis handles thermal compensation, while the w-axis controls the bondline thickness (BLT). Given the bondhead assembly's substantial mass, there can be a slight delay between braking and actual movement stop, potentially causing damage, especially in fine pitch applications with minimal solder volume. To address this, high-sensitivity force sensors can be used, although their placement near the bond tip is challenging. An alternative approach is employing a bondhead with an additional, highly sensitive z-axis with less mass, improving accuracy and control.

Furthermore, ensuring parallelism between the die and substrate is achieved through calibration schemes and real-time checks by the independent actuators for x and y movements in the bondhead. This capability is essential for handling large dies with fine pitches.

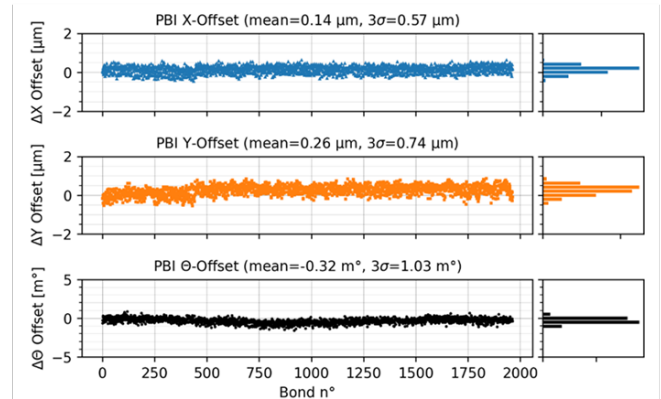
A key element in achieving high accuracy is the precise alignment of the various modules. This equipment utilizes high-quality optics and cameras to ensure exceptional performance. All cameras are equipped with global shutters to prevent aberration defects and motion blur. The integration of high-resolution camera systems, with capabilities as fine as 0.63 $\mu\text{m}/\text{pixel}$, and the use of telecentric lenses have significantly enhanced accuracy.

Unlike conventional lenses, which exhibit parallax or perspective errors due to their angular fields of view—where magnification decreases as the distance between the lens and object increases—telecentric lenses offer a constant, non-angular field of view. This means that within their depth of field, telecentric lenses maintain the same field of view, eliminating perspective distortions. Additionally, telecentric lenses typically have lower distortion values compared to

conventional lenses, resulting in sharper images and more accurate measurements (adapted from [8]).

Combined with advanced algorithms developed internally for bump detection and exclusion based on user-defined parameters, the vision system is both robust and state-of-the-art.

$\pm 0.75\mu\text{m}@3\sigma$ & $\pm 1.05\text{m}^\circ@3\sigma$



$\pm 0.5\mu\text{m}@3\sigma$ & $\pm 1\text{m}^\circ@3\sigma$

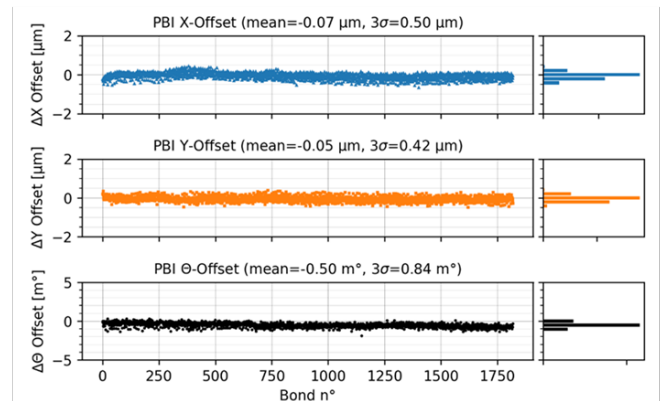


Figure 7. Accuracy measurements using 30x20mm glass die with 1800 placements: robust data (top), champion data (bottom).

Both the substrate camera and uplooking camera, positioned inside the tunnel, are exposed to elevated temperatures, which can lead to image aberrations or haze. These distortions significantly impact alignment accuracy by warping and altering the captured images. To address this issue, an inert gas like nitrogen is introduced to counteract the temperature-induced distortions without affecting the tunnel's internal conditions. As shown in Figure 12, enabling this method reduces the 3 sigma search error from nearly 2 μm to just 90 nm, greatly enhancing alignment precision.

To meet the demands of bonding devices at a 10 μm pitch, maintaining cleanliness is essential. Particles can easily become trapped between Cu pillars, potentially causing shorts if they are metallic, or between the Cu pillar and Cu bond pad, which can lead to open circuits. The equipment discussed in this article achieves ISO5 cleanliness levels through several key advancements. These include:

- Mechanical Module Design: Intelligent redesigns and protective shielding minimize particle generation from the mechanical modules.
- Air Stream Monitoring: Careful control of the air stream within the tunnel ensures a steady flow, avoiding turbulence and stagnant zones.
- Effective Exhaust Capabilities: Proper exhaust systems address outgassing issues, particularly during TCB processes involving flux or NCF.
- Enclosed Processing Space: The use of an enclosed tunnel space for processing both the substrate wafer and components significantly reduces particle contamination.

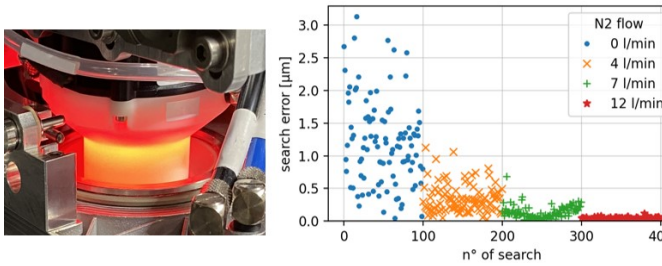


Figure 8. Nitrogen flow attachment at substrate camera.

These developments collectively contribute to a cleaner environment, essential for achieving high-precision bonding at such fine pitches.

A critical aspect of TCB is applying heat to achieve temperatures typically exceeding 300°C. At these high temperatures, material expansion is expected, which can significantly impact machine accuracy. Key factors include:

- Machine Expansion: Movement in the die holder tool or nozzle due to the machine's own thermal expansion.
- Die Expansion: The die expands based on its material properties, RDL concentration and distribution, and the uniformity of heat application by the nozzle. Uneven heating can cause parts of the die to experience different expansion rates.

A test was conducted to monitor the expansion of both the die and the nozzle during heat ramp-up, using a built-in uplooking camera. The temperature range tested was from 50°C to 350°C, typical for TCB.

Figure 9 illustrates the expansion in eight parameters: four corners of the die/nozzle in both x and y directions. A 31x20mm die was used in conjunction with a 33x23mm nozzle. Figure 9 (top) shows the expansion of the four die corners in x and y directions. The results indicate symmetrical expansion on both the left and right sides of the die, with the x dimension exhibiting more expansion due to the die's rectangular shape. The expansion magnitude at 350°C is consistent across the left and right sides of the die.

Figure 9 (bottom) presents similar measurements for the nozzle. Due to differing materials, the nozzle experiences a higher expansion rate and magnitude because of its higher coefficient of thermal expansion (CTE). This is a very important result because it shows that the heating is homogenous not only at steady state but also during ramping. If the heating was not uniform hotspots might cause the die to

expand more in one direction than the other causing an accuracy issue.

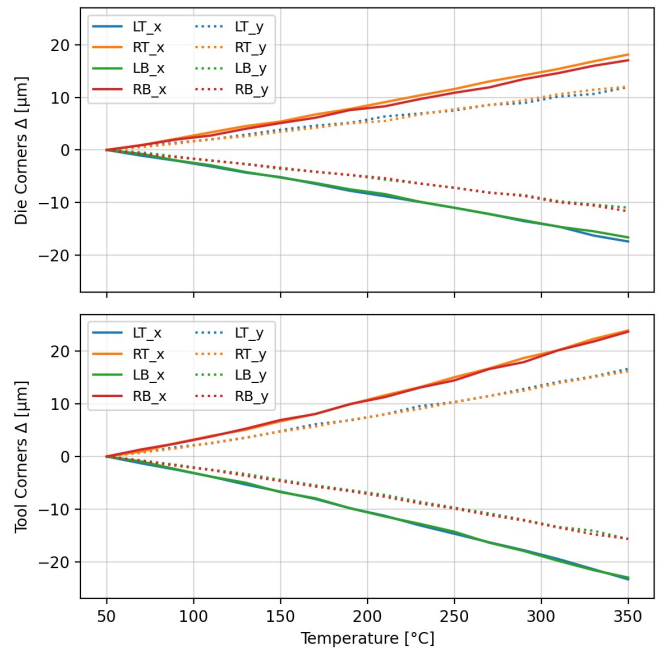


Figure 9. Die and tool expansion on TCB Bondhead.

In advanced packaging, particularly with smaller node chiplets, material costs are high, making yield control critical. The system features a traceability function that monitors and records key bonding parameters to identify patterns in failed test results and apply predictive algorithms.

Figure 10 illustrates this with a TCB programmed profile on the left and an actual bond profile on the right. The visual representation highlights the numerous parameters that can be tracked and compared between different bonds. However, the actual data exportable is significantly more extensive, tailored to customer specifications.

In the bond profile shown in Figure 10 (top), the process begins with the die and substrate making initial contact. A constant force is applied (blue line) while the temperature is raised above the solder's melting point (red line). The high-dynamic w-axis (light green) compensates for any thermal expansion in the material or bonder modules. As the solder bumps begin to collapse during melting, resistance drops sharply. This change is detected by a position shift in the w-axis, which adjusts within milliseconds to prevent solder squeeze-out (Figure 10 bottom). The collapse is followed by a force profile defined in the bond recipe, ensuring precise control over the bonding process.

Stacking

While TCB is widely used for assembling CPUs, datacenter logic dies, GPUs, and accelerators, High Bandwidth Memory (HBM) presents some of the most demanding requirements. With the recent adjustment of packaging standards allowing HBM package heights to increase from 725µm to 775µm, the industry is progressing towards 16Hi HBM configurations with TCB. This shift introduces significant challenges due to shrinking bump pitches and the complexities associated with stacking 16

DRAM dies. These challenges include managing warpage and internal stresses within the stack. As high-end applications increasingly adopt HBM configurations with up to 16 stacks, the market potential is substantial, but mastering the associated HVM (High Volume Manufacturing) challenges is crucial.

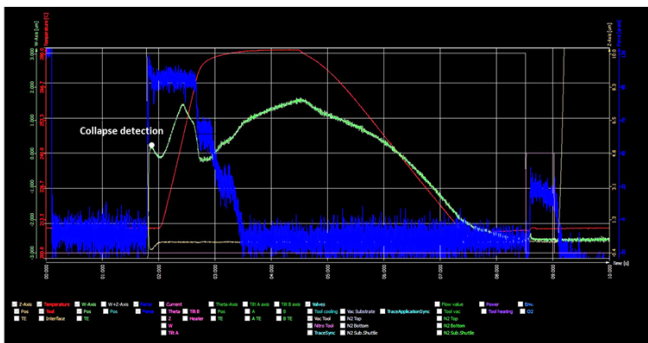
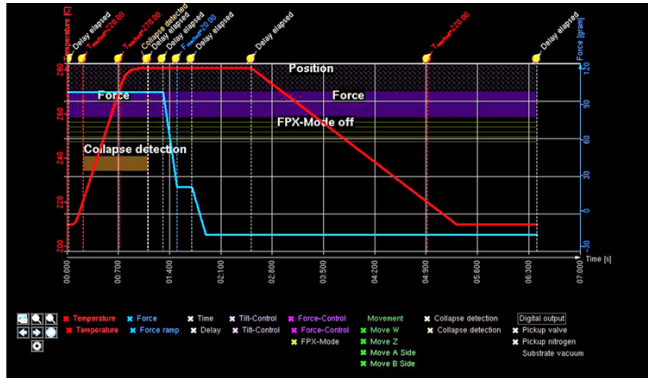


Figure 10. TCB profile as programmed (top), and actual TCB profile with readouts from sensors (bottom).

Handling extremely thin dies, especially those below 50µm in thickness, presents a significant challenge. Thin die handling with Through-Silicon Vias (TSVs) and copper pillars has been successfully demonstrated at a thickness of 35µm using specially designed ejection tools within TC systems. The roadmap is now set for achieving thicknesses below 25µm, with ongoing development of advanced ejection and pickup technologies in collaboration with key material suppliers.

Conclusions

This paper has emphasized the critical role of TCB both today and in the future, highlighting the industry's and research institutions' significant efforts to push the technology down to 10µm pitches. A promising application of TCB is in interposer attachment, where, despite not involving fine pitches, it is essential to hold the interposer securely during reflow and solder solidification to manage warpage effects.

The development of no-flux TCB represents a major advancement, tackling the limitations imposed by flux and films in achieving a robust and reliable bonding process. We have shown successful no flux TC bonding via hydroxyl reduction through cross sections. Heat homogeneity was also verified through measurements of the die and nozzle whilst ramping up temperature, verifying that both die and nozzle

expand linearly, although at different rates due to differences in the material CTE.

A $\pm 0.5\mu\text{m}$ @ 3σ was also demonstrated over 1800 placements. An actual TCB profile was compared to the programmed one, showing the equipment's capability to follow closely and react rapidly to ensure the bonding sequence is optimal. On the note of accuracy, the design and implementation of the nitrogen delivery module to the substrate camera area has shown a drastic improvement in 3 sigma search error from 2µm to 90nm. Finally the homogeneity and linearity of the heating on the tool and die has been proven by measuring the 4 corners of too and die respectively during heat ramping.

Although alternative interconnect schemes have already reached sub-10µm pitches, solder interconnects remain crucial for connecting assembled systems to substrates or PCBs. Advanced mass reflow and TCB continue to be the reference solutions for these needs. With the ongoing trend towards finer pitches, it is evident that TCB will remain a cornerstone technology in the field.

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