

Article

Simulation Study on the Micro Chip Mounting Technology on Complex Curved Surfaces by Anisotropic Conductive Adhesive

Shan Jiang ^{1,2}, Bin Xie ³, Long Bai ^{1,2} and Pin Zhang ^{1,2,*}

¹ Aviation Key Lab of Science and Technology on High Performance Electromagnetic Windows, Ji'nan 250023, China; jiangs060@avic.com (S.J.); bail008@avic.com (L.B.)

² Innovation Center for Electromagnetic Functional Structure, Ji'nan 250023, China

³ School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

* Correspondence: zhangp016@avic.com; Tel.: +86-0531-85665060

Abstract

To investigate the influence of substrate curvature and process deviations on the bonding quality of microchips mounted on curved surfaces, a thermo–mechanical coupled finite element model was developed in ANSYS 19.2 using a 0402 microchip as a representative component. The model was employed to evaluate the effects of substrate curvature radius, chip placement position, chip angular misalignment, and thermocompression-head angular deviation on the stress distribution and bonding behavior during conformal assembly. The simulation results were further validated through thermocompression bonding experiments. The results show that decreasing the substrate curvature radius significantly increases the stress concentration in the chip-pad region and leads to a more non-uniform stress distribution. In addition, placement errors and loading-direction deviations adversely affect bonding quality by altering the contact stress distribution and increasing the tendency for chip displacement and sliding. Quantitative analysis reveals the relative sensitivity of bonding performance to different geometric and process parameters, providing insight into the dominant thermo–mechanical mechanisms governing curved-surface assembly. Experimental results further demonstrate that excessive thermocompression tilt angles can significantly reduce bonding strength and increase chip sliding, suggesting that the tilt angle should be controlled within an appropriate range to ensure assembly reliability. The proposed thermo–mechanical modeling approach provides a quantitative tool for evaluating the influence of process variations on curved-surface microchip assembly and offers practical guidance for process parameter selection, tolerance control, and reliability-oriented design of conformal electronic packaging.

Keywords: curved circuit; surface mounting; microchips; thermo–mechanical coupling; finite element simulation; process window



Academic Editor: Francesco Giuseppe Della Corte

Received: 30 April 2026

Revised: 15 June 2026

Accepted: 2 July 2026

Published: 21 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

With the continuous advancement of semiconductor technology, conventional planar assembly techniques have become increasingly inadequate to meet the growing demands of emerging applications [1,2]. Ranging from aircraft skins and radar detection systems related to national security to flexible electronic displays and wearable devices widely used in civilian fields, conformal assembly on curved surfaces, as a critical process in surface packaging, has attracted extensive attention from researchers worldwide [3–6]. Current approaches to chip assembly on curved or non-planar substrates mainly include transfer

printing techniques, robotic pick-and-place assembly, anisotropic conductive adhesive (ACA)-based thermocompression bonding, and laser-assisted local bonding technologies [7–11]. Transfer printing methods are widely used in flexible electronics due to their excellent conformability; however, their alignment accuracy and large-area integration capability remain limited. Robotic assembly systems combined with machine vision and multi-degree-of-freedom motion platforms can achieve high-precision placement on curved surfaces, but they generally suffer from low manufacturing efficiency and high system complexity. ACA-based thermocompression bonding has attracted increasing attention because of its low-temperature interconnection capability and compatibility with miniaturized electronic packaging [12–14]. Typical failure modes in curved-surface chip assembly include chip sliding, pad misalignment, interfacial delamination, local stress concentration-induced cracking, and conductive failure of the ACA layer caused by insufficient contact stability [15–18]. In particular, the coupling effect between substrate curvature and thermocompression loading may significantly aggravate interfacial shear stress and stress non-uniformity, thereby reducing packaging reliability [19–23]. Therefore, understanding the thermo-mechanical behavior and failure mechanisms during curved-surface bonding is essential for process optimization and reliable conformal packaging. However, systematic studies on high-precision chip assembly processes for curved substrates remain limited, and related technologies and equipment in China are still at an early stage of development. Therefore, to support the independent development of advanced manufacturing technologies and equipment, there is an urgent need to establish mature and reliable conformal chip assembly processes for curved surfaces. Compared with planar assembly, surface curvature not only reduces the efficiency of solder encapsulation but also amplifies the adverse effects of process parameter deviations on assembly quality. Consequently, to reduce process development costs and optimize assembly performance, it is necessary to conduct finite element simulations of the curved-surface thermocompression bonding process to realistically reproduce practical conditions, investigate the effects of key parameters on bonding quality, and determine the process window boundaries for conformal assembly on curved substrates.

Lau et al. [24] conducted simulation analyses of ball grid array (BGA) packaging using computational fluid dynamics (CFD) and finite element software, and proposed a general finite element simulation methodology to investigate solder joint stress distributions and potential defects induced during solder phase transformation. However, the solder materials considered in their study were conventional metallic alloys, whose mechanical behaviors differ significantly from those of conductive adhesives. K. N. Chiang et al. [25] employed nonlinear finite element simulations to investigate the assembly process using anisotropic conductive adhesive (ACA), and developed a one-dimensional equivalent spring model to significantly reduce CPU computation time. Their work further examined the effects of processing conditions, such as thermocompression temperature and applied load, on assembly quality. Nevertheless, this study primarily focused on the mechanical behavior of microscale conductive particles within the ACA under compressive loading, while the influence of process parameters on the macroscopic force transfer and stress distribution between the conductive adhesive and the chip was not comprehensively addressed.

In the present study, a thermo-mechanical coupled finite element model is established based on the ANSYS 19.2 Workbench platform to systematically investigate the effects of surface curvature and other key process parameters on chip assembly quality. In this study, a 0402 packaged chip was selected as the representative component because it is one of the most widely used miniature surface-mounted devices in flexible electronics, wearable systems, and high-density conformal circuits. Due to its small geometric dimensions and

high sensitivity to positional deviation and interfacial stress concentration, the 0402 chip provides a suitable platform for investigating the influence of substrate curvature and process parameters on curved-surface thermocompression bonding behavior.

2. Bonding Materials and Processes

Anisotropic conductive adhesive (ACA) has been extensively adopted in miniaturized and high-density electronic packaging owing to its environmental friendliness, low processing temperature, and cost effectiveness. Compared with conventional metallic solder alloys, ACA enables finer interconnection pitch, simplified bonding processes, and reduced thermal budget, thereby improving packaging efficiency and manufacturing yield [26]. Owing to its intrinsic anisotropic electrical characteristics, ACA provides electrical insulation in the in-plane directions (x – y) while ensuring electrical conductivity in the through-thickness direction (z), which significantly relaxes the requirements for precise adhesive dispensing. In practice, uniform coating of ACA on the bonding pads is sufficient to achieve reliable interconnection.

A schematic illustration of the ACA bonding process is shown in Figure 1. Under the combined effects of applied pressure and thermal loading, the adhesive deforms, allowing conductive particles within the ACA to establish vertical contact between the chip pads and substrate electrodes. During curing, volumetric shrinkage of the adhesive increases the compressive contact force on the conductive particles, leading to the formation of stable electrical conduction paths [26,27]. Consequently, the electrical interconnection in ACA-based assemblies is governed primarily by the deformation behavior of conductive particles under contact pressure. The electrical and mechanical reliability of the joint is strongly dependent on the local contact stress and effective contact area. Therefore, enhanced contact stability and sufficient bonding pressure are critical factors in improving the reliability of ACA interconnections [28,29].

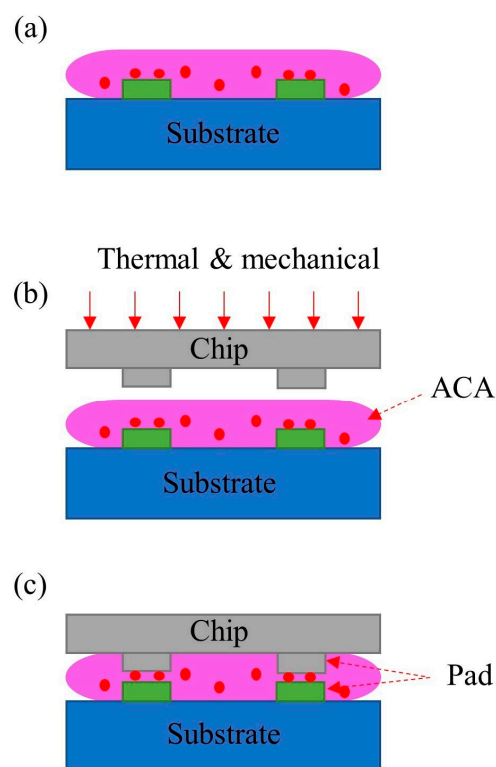


Figure 1. Schematic diagram of the ACA bonding principle. (a) ACA coating; (b) Thermocompression; (c) End of bonding.

3. Finite Element Modeling

3.1. Geometric Modeling

To address the technical requirements of conformal chip assembly on curved surfaces, a finite element model consisting of the thermocompression head, chip, solder material, bonding pads, and curved substrate was established. The objective of this model is to elucidate the effects of substrate curvature and key process parameters on interfacial thermal stress distribution and stress concentration during the thermocompression bonding process, thereby providing quantitative guidance for process optimization and design improvement.

In this study, a 0402 packaged chip with dimensions of 1 mm × 0.5 mm was selected as the representative component, while the substrate was modeled as a cylindrical surface with a prescribed curvature. Subsequent analyses investigate the influence of varying substrate curvature radii and process parameters on bonding quality. As a representative case, a substrate curvature radius of 5 mm was considered, with no lateral or angular misalignment of the chip and with the thermocompression force applied along the surface normal direction. The corresponding geometric model was constructed using SolidWorks 2025 and is illustrated in Figure 2.

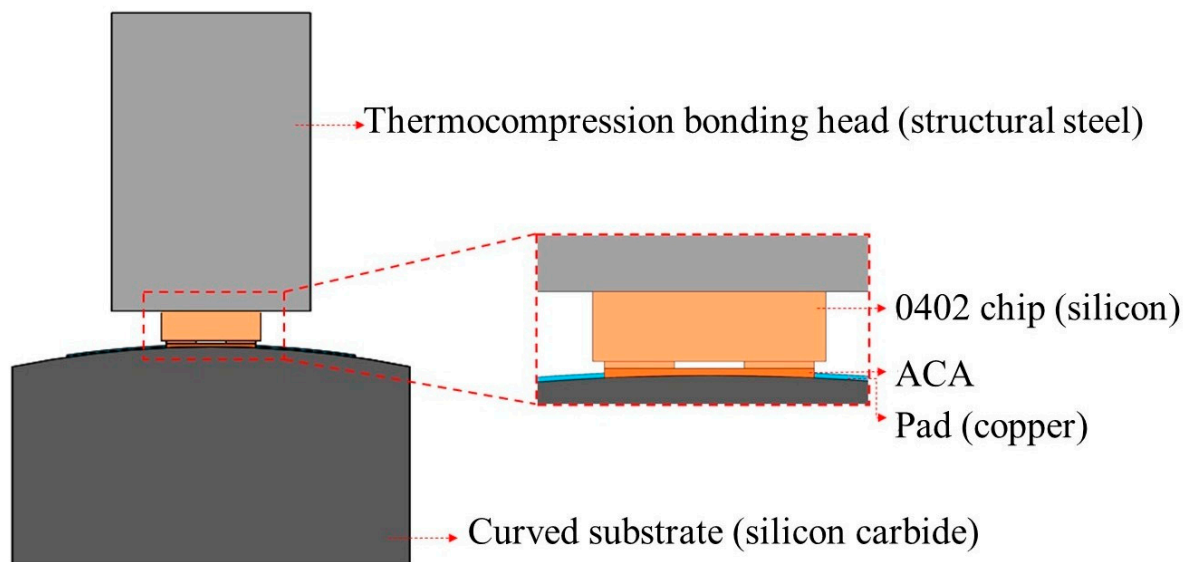


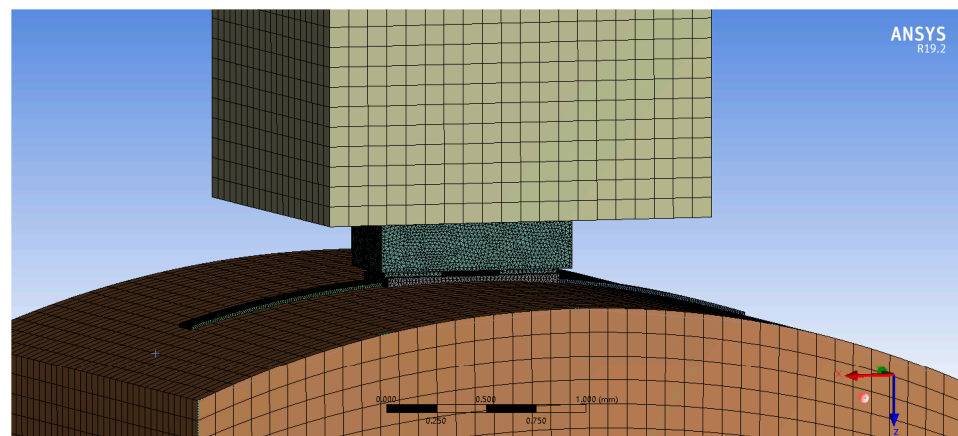
Figure 2. Geometric model of conformal mounting on a curved surface.

Conformal assembly on curved surfaces involves the simultaneous application of thermal loading and mechanical pressure, and therefore constitutes a thermo-mechanically coupled problem. Accordingly, the steady-state thermal and steady-state structural modules in ANSYS 19.2 Workbench were employed to perform the coupled analysis. The three-dimensional geometric model was imported into ANSYS 19.2 Workbench, and the material properties of each component were assigned as listed in Table 1 [5].

A sweep meshing strategy was employed for the imported model. Since the chip and the anisotropic conductive adhesive (ACA) were the primary objects of interest, local mesh refinement was applied to these regions to improve computational accuracy. After meshing, the model consisted of 143,144 elements and 370,176 nodes. The meshed model is shown in Figure 3.

Table 1. Material property settings for the simulation analysis.

Material	Density (kg/m ³)	Thermal Conductivity (W/m·°C)	Specific Heat Capacity (J/kg·°C)	Elastic Modulus (GPa)	Poisson's Ratio	Coefficient of Thermal Expansion (×10 ^{−6} /°C)
Thermocompression bonding head	7850	60.5	460	200	0.3	12
Chip	2330	120	708	129	0.28	2.6
ACA	1550	0.43@21 °C	1100@21 °C	3.30@21 °C	0.42@21 °C	45@21 °C
		0.47@100 °C	1250@100 °C	1.65@100 °C	0.43@100 °C	65@100 °C
		0.51@140 °C	1500@140 °C	0.8@140 °C	0.45@140 °C	85@140–190 °C
		0.56@190 °C	1500@190 °C	0.8@190 °C	0.45@190 °C	
Pad	8933	400	390	130	0.3	16.5
Substrate	3100	120	710	300	0.35	4.0

**Figure 3.** Geometric model after mesh generation.

3.2. Constraints and Boundary Conditions

Conformal mounting on curved substrates involves large deformation of the anisotropic conductive adhesive (ACA), rendering the process highly nonlinear. To ensure the accuracy of the numerical results and to improve the convergence of the model, the following constraints and boundary conditions were applied in the simulation:

1. All interfaces in the model were defined as frictional contacts. Appropriate friction coefficients were assigned according to the contacting material pairs. An asymmetric contact formulation was adopted, and the Lagrange multiplier method was selected as the contact algorithm.
2. The initial temperature of the thermocompression bonding head was set to 200 °C, while the initial temperatures of all other components and the ambient environment were set to 22 °C. Convective heat transfer with air was applied to all surfaces except the direct contact interface of the bonding head, with a convection coefficient of 10 W m^{−2} K^{−1}. Thermal radiation was neglected due to the relatively low heating temperature and heat generation power of the bonding head.
3. The temperature field obtained from the thermal analysis was fully imported into the subsequent static structural analysis to account for thermomechanical coupling effects.
4. A fixed constraint was applied to the bottom surface of the substrate, while a pressure load of 12.5 MPa was applied to the top surface of the thermocompression bonding head.

The detailed simulation parameters and boundary conditions used in the finite element model are summarized in Table 2.

Table 2. Simulation Parameters and Boundary Conditions.

Parameter	Value	Description
Chip size	1 mm × 0.5 mm	Silicon chip dimensions
Pad size	0.25 mm × 0.30 mm	Upper/lower pad dimensions
ACA thickness	0.025 mm	Initial adhesive layer thickness
Thermocompression temperature	200 °C	Initial temperature of bonding head
Ambient temperature	22 °C	Initial environmental temperature
Contact type	Frictional contact	Applied to all contact interfaces
Friction coefficient (head/chip)	0.15	Frictional interaction parameter
Friction coefficient (chip/ACA)	0.20	Frictional interaction parameter
Friction coefficient (ACA/pad)	0.30	Frictional interaction parameter
Thermal convection coefficient	10 W·m ^{−2} ·K ^{−1}	Natural convection condition

4. Simulation Results and Analysis

4.1. Temperature Field Simulation Results

The primary objective of the thermocompression process was first clarified. During thermocompression bonding, heat is transferred from the bonding head through the chip to the ACA layer, while simultaneously inducing a thermal effect on the substrate. This process is governed predominantly by heat conduction and convective heat transfer mechanisms. Based on the modeling assumptions and boundary conditions described above, thermal simulations were performed. After the temperature field reached a steady state, the temperature distributions of the individual components were obtained, as shown in Figure 4.

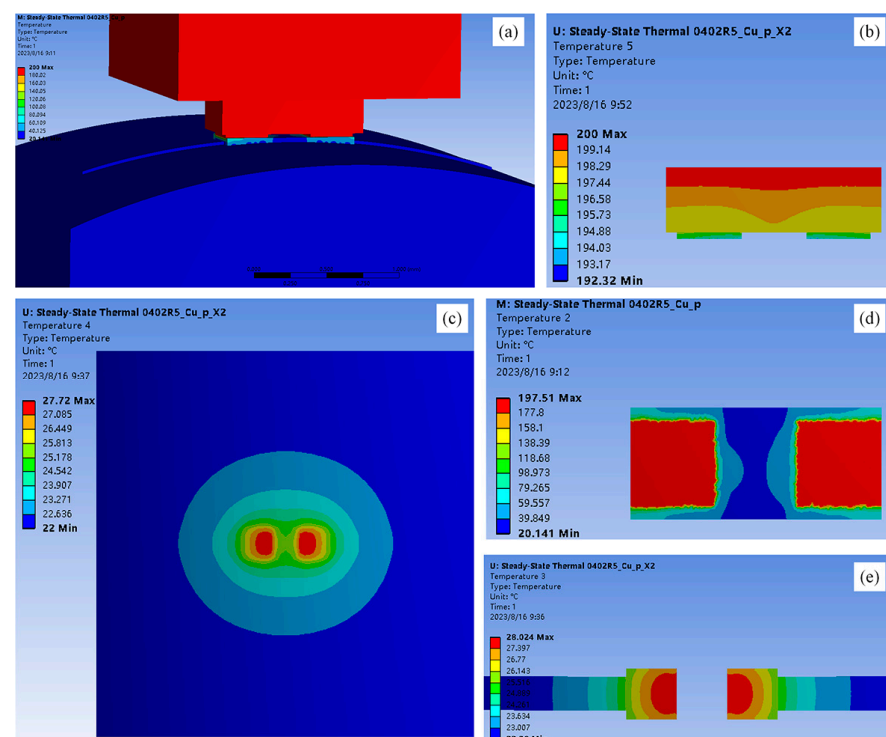


Figure 4. Results of the steady-state thermal simulation. (a) The whole simulation domain; (b) The micro chip domain; (c) The substrate domain; (d) The bottom surface of the micro chip; (e) The copper layer.

As illustrated in the figure above, the temperature gradually decreases during heat transfer from the thermocompression bonding head to the substrate. Owing to the low thermal conductivity of the ACA, a pronounced temperature gradient is observed across the ACA layer, with temperatures ranging from approximately 20.1 °C to 197.5 °C. Such a significant temperature difference results in spatially varying material properties of the ACA along the thickness direction, which subsequently leads to nonuniform deformation behavior in the static structural analysis.

4.2. Thermo-Mechanical Simulation Results and Analysis

The temperature field obtained from the steady-state thermal simulation was imported into the steady-state structural analysis module. Based on the boundary conditions defined in the previous section, a thermo-mechanical stress analysis was performed to evaluate the thermal stress distribution within the model. The resulting stress contour of the anchored chip after thermocompression bonding is shown in Figure 5.

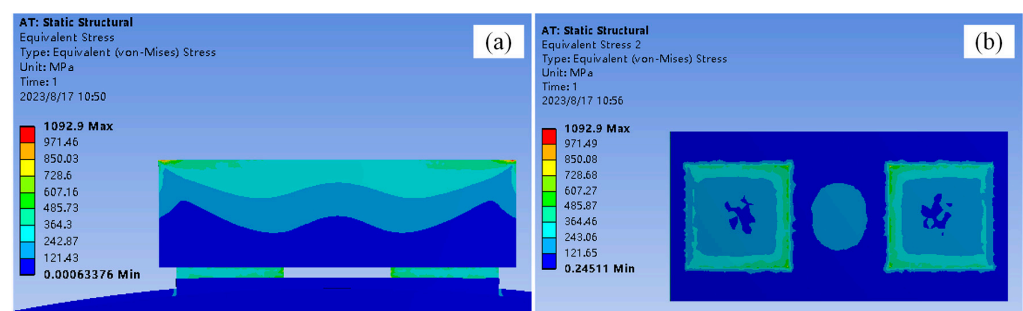


Figure 5. Stress contour of the anchored chip: (a) front view; (b) bottom view.

As shown in Figure 5, the maximum stress experienced by the chip reaches approximately 1.1 GPa, with stress predominantly concentrated at the solder pad region on the bottom surface of the chip. Owing to the presence of substrate curvature, the stress distribution across the chip–pad interface is markedly non-uniform. Specifically, stress concentration occurs mainly on the inner side of the pad, i.e., the side closer to the apex of the curved substrate. For ACA-based bonding systems, higher packaging reliability is strongly associated with stable interfacial contact and sufficiently high bonding stress. Excessive stress concentration at the chip pads may not only exceed the mechanical strength limits of the chip, leading to potential damage or failure, but also indicate poor contact stability, which is detrimental to the overall bonding quality. In the following sections, the effects of varying substrate curvature and key process parameters on the curved-surface thermocompression bonding process will be systematically investigated to further elucidate their influence under different operating conditions.

4.3. Effects of Process Parameters

4.3.1. Substrate Curvature

To investigate the influence of substrate curvature on the curved-surface thermocompression bonding process, three substrates with different curvature radii were designed and analyzed in this study. The selected curvature radii were 10 mm, 5 mm, and 2 mm. For all cases, the minimum thickness of the applied ACA bonding layer was maintained within the range of 0.02–0.03 mm. The temperature of the thermocompression bonding head was fixed at 200 °C, and a normal pressure of 12.5 MPa was uniformly applied to the upper surface of the bonding head. No positional or angular misalignment of the chip was introduced during placement. After simulation, the stress distributions at the chip solder

pads corresponding to the different substrate curvature radii were obtained, as shown in Figure 6.

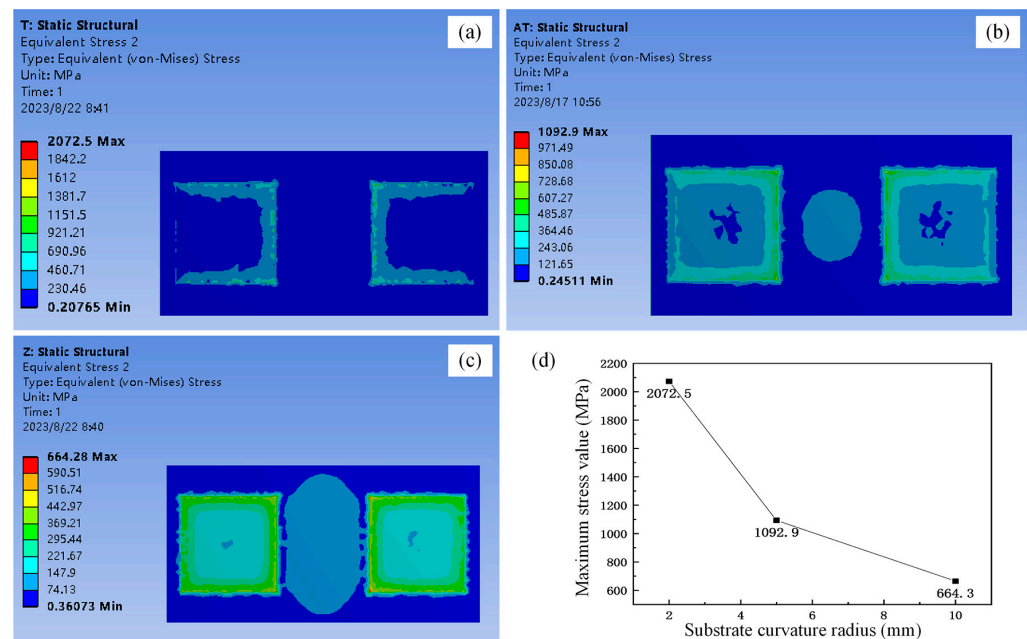


Figure 6. Stress contours of the chip under different substrate curvature radii. (a) $R = 2$ mm; (b) $R = 5$ mm; (c) $R = 10$ mm; (d) Variation of maximum stress value with increasing substrate curvature radius.

As indicated by the results in Figure 6, when the substrate curvature radius is relatively large, the curved-surface bonding process approaches that of planar bonding. Under this condition, the maximum stress is relatively low and the stress distribution at the chip solder pads is more uniform, indicating improved compression uniformity of the ACA. This results in a larger effective conductive contact area and enhanced contact stability, thereby contributing to higher packaging reliability.

As the curvature radius decreases from 10 mm to 2 mm, the maximum stress increases significantly from 664.2 MPa to 2072.5 MPa. However, the peak stress becomes increasingly concentrated at the inner side of the solder pads, and the degree of stress concentration intensifies with further reduction in curvature radius, which adversely affects the bonding quality. If excessive thermocompression pressure is applied, severe stress concentration may occur at the inner region of the solder pads, potentially leading to chip damage. Conversely, insufficient pressure fails to ensure adequate compression of the ACA over most regions outside the stress concentration zone, resulting in a reduced conductive contact area and poor contact stability, which ultimately compromises the bonding quality.

4.3.2. Chip Angular Misalignment

To further investigate the influence of process parameters on bonding quality, a series of comparative finite element simulations were conducted. This subsection focuses on the effect of chip angular misalignment on the bonding performance. The simulation case with a substrate curvature radius of 5 mm, no positional or angular misalignment, and a normal thermocompression pressure of 12.5 MPa was selected as the reference condition. Based on this baseline, an additional simulation was performed in which only a 5° angular misalignment was introduced to the chip during placement. The comparative stress distribution results are presented in Figure 7.

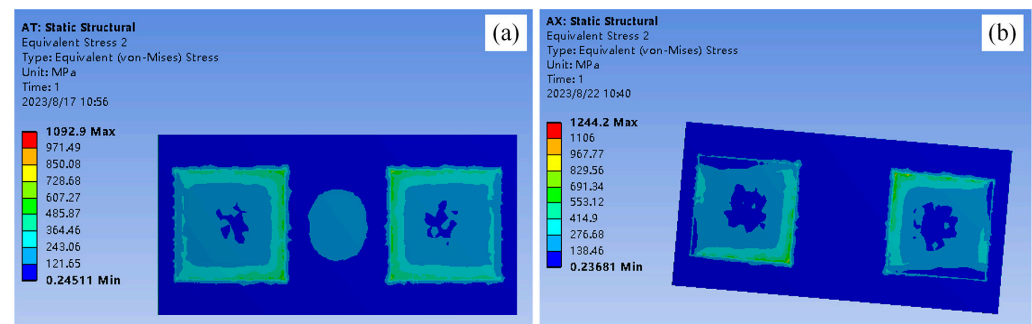


Figure 7. Stress distribution with chip angular misalignment. (a) 0° angular misalignment; (b) 5° angular misalignment.

As shown in Figure 7, when a 5° angular misalignment is introduced during chip placement, the maximum von Mises stress increases from 1092.9 MPa to 1244.2 MPa. This increase can be attributed to the alignment error between the chip pads and the substrate pads caused by the angular deviation. Under a constant applied pressure, the effective contact area is reduced, resulting in a higher stress concentration. Moreover, the stress distribution becomes more non-uniform, with peak stress localized at the pad corners. Such stress concentration further reduces the effective conductive contact area, which is detrimental to the formation of stable electrical interconnections and ultimately compromises the packaging reliability.

4.3.3. Lateral Misalignment of the Chip

To further investigate the influence of lateral misalignment on the conformal bonding process, the simulation case with a substrate curvature radius of 5 mm, no angular or positional deviation, and a normal applied pressure of 12.5 MPa was selected as the reference condition. Based on this baseline, a series of simulations were conducted with chip lateral offsets of 0.025 mm, 0.05 mm, and 0.075 mm, respectively. The corresponding stress distribution results are presented in Figure 8, while the variation in the maximum stress as a function of lateral offset distance is summarized in Figure 9.

As indicated by the results in the above figures, increasing the chip placement offset from 0 to 0.075 mm leads to a progressively larger misalignment between the chip pads and the substrate pads. Assuming that both the upper and lower pads have identical dimensions of $l \times l$ and the lateral offset is Δx , the effective contact area can be expressed as $l \times (l - \Delta x)$. This relationship indicates that positional misalignment reduces the total load-bearing contact area, resulting in an increase in the maximum stress experienced by the chip from 1.1 GPa to 1.58 GPa, while simultaneously decreasing the effective conductive contact area and thereby degrading the bonding quality.

Further examination of the stress contour plots reveals that the overall stress uniformity on the chip pads is not significantly affected under small lateral offsets, and stable conductive contact can still be maintained to ensure normal post-bonding operation of the chip. However, as the offset distance increases, the maximum stress becomes concentrated on one side of the pad, leading to asymmetric load distribution, which may accelerate chip degradation and increase the risk of mechanical failure.

4.3.4. Pressure Misalignment Angle

In practical bonding processes, deviations may occur between the applied thermo-compression force direction and the surface normal of the substrate. To investigate the influence of pressure misalignment on the bonding performance, a reference case was first established with a substrate curvature radius of 5 mm, zero positional and angular chip

misalignment, and a purely normal applied pressure of 12.5 MPa. Based on this reference condition, the effect of thermocompression force deviation was analyzed.

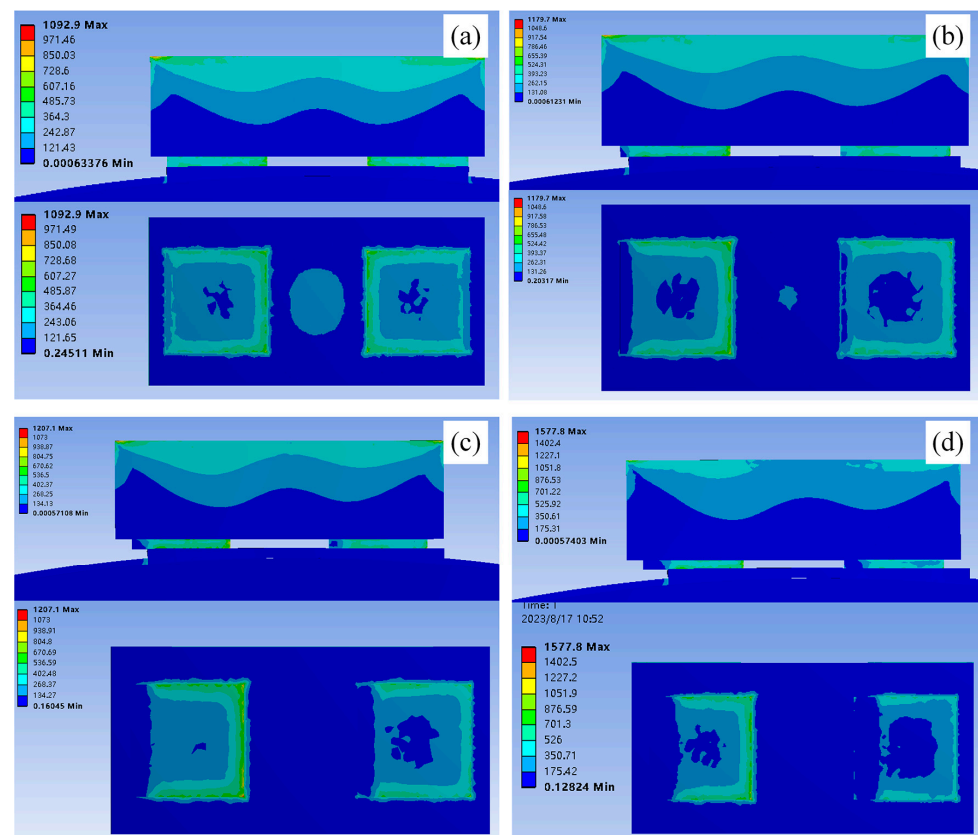


Figure 8. Stress distribution with chip lateral offset. (a) 0 mm; (b) 0.025 mm; (c) 0.05 mm; (d) 0.075 mm.

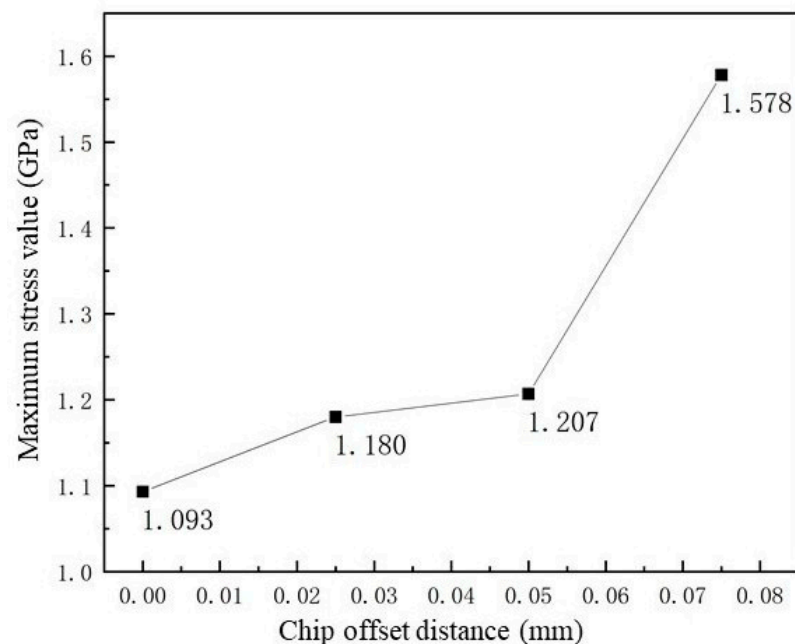


Figure 9. Variation in maximum stress with different lateral offset distances.

Two representative loading cases were considered: (i) a normal pressure of $P_z = 12.5$ MPa combined with a lateral pressure component of $P_x = 1.25$ MPa, and (ii) a normal

pressure of $P_z = 12.5$ MPa combined with a lateral pressure component of $P_x = 2.5$ MPa. The corresponding simulation results are presented in Figure 10.

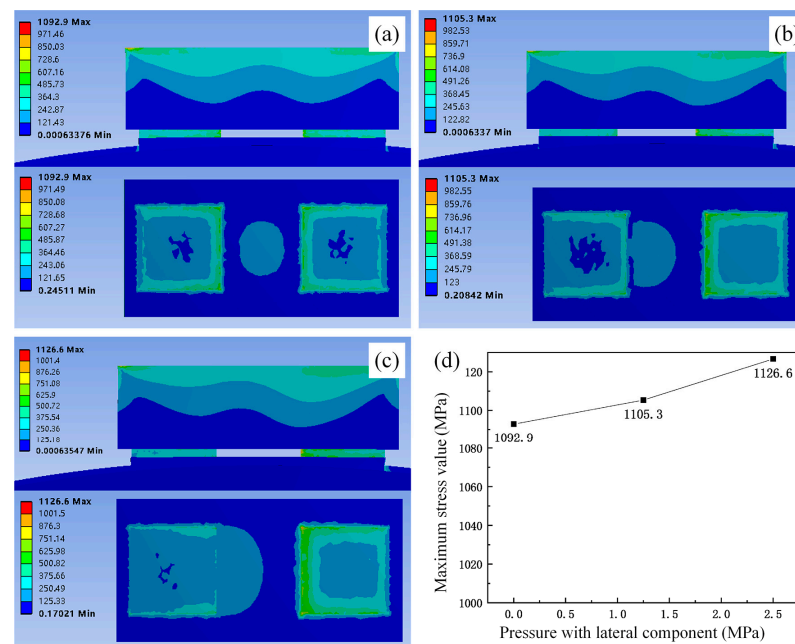


Figure 10. Chip stress distribution under a tilted thermocompression loading direction ($P_z = 12.5$ MPa). (a) $P_x = 0$ MPa; (b) $P_x = 1.25$ MPa; (c) $P_x = 2.5$ MPa; (d) Variation of maximum stress value with increasing lateral pressure.

Because the thermocompression force misalignment does not introduce pad misregistration, the total effective contact area between the upper and lower pads remains unchanged; consequently, the overall magnitude of the applied stress is largely preserved. However, the misalignment significantly affects the uniformity of the stress distribution. Analysis of the stress contour maps reveals that when the thermocompression force is inclined toward the positive x -direction, the pads located on the negative x -side experience lower stress, whereas those on the positive side are subjected to higher and more uniformly distributed stress. This asymmetric stress distribution leads to pronounced differences in electrical contact behavior between the opposing pads. As a result, satisfying the bonding conditions on the positively loaded side does not necessarily guarantee adequate bonding on the negatively loaded side. Furthermore, the presence of a lateral force component induces a tendency for in-plane chip sliding. Although the anisotropic conductive adhesive (ACA), serving as the bonding medium, provides a certain level of resistance to sliding, excessive force misalignment may still result in chip displacement or even lateral tilting. Such phenomena pose significant challenges to the stability and reliability of the thermocompression bonding process.

In summary, this study systematically analyzes the effects of key process parameters—including substrate curvature, chip angular misalignment, lateral positional offset, and thermocompression force misalignment—on the bonding quality in conformal surface assembly. More importantly, a detailed finite element simulation methodology and procedural framework are established. Based on this approach, the adaptability of anchored chips to various curved substrates can be thoroughly evaluated, and the maximum tolerable process parameter deviations under different manufacturing precision requirements can be quantitatively determined. These findings delineate the process window boundaries for curved-surface thermocompression bonding and provide valuable guidance for the design and optimization of conformal bonding processes.

5. Thermocompression Experimental Analysis

It should be noted that the finite element results represent local thermo–mechanical stress fields, which cannot be directly measured in experiments. Therefore, experimental validation is performed through measurable macroscopic responses such as chip displacement, angular deviation, and bonding strength, which serve as indirect but quantitative indicators of the underlying stress evolution predicted by the simulation. Based on the preceding thermo–mechanical coupled simulation analysis, thermo-compression experiments on curved surfaces were conducted using a thermocompression bonding head to further elucidate the practical process behavior and underlying mechanisms of chip bonding under curved conditions. In the experiments, the thermocompression system was first adjusted to a preset thermocompression tilt angle. Subsequently, the processes of adhesive dispensing, chip placement, and thermocompression bonding were carried out sequentially. After bonding, the morphological characteristics of the 0402 chips were measured and analyzed to evaluate their displacement, angular deviation, and interfacial stability, thereby enabling a quantitative comparison with the simulation predictions through these macroscopic response parameters.

The experimental results are shown in Figure 11. Within a thermocompression tilt angle range of 0–12°, the post-bonding positioning accuracy and displacement behavior of the chips were systematically investigated. The results indicate that the thermocompression tilt angle has a pronounced influence on the final placement position and interfacial stability of the chips. When the tilt angle is smaller than 4°, the chips maintain good positional stability on the substrate, and no obvious offset or sliding is observed, demonstrating that both alignment accuracy and interfacial bonding requirements can be simultaneously satisfied within this range.

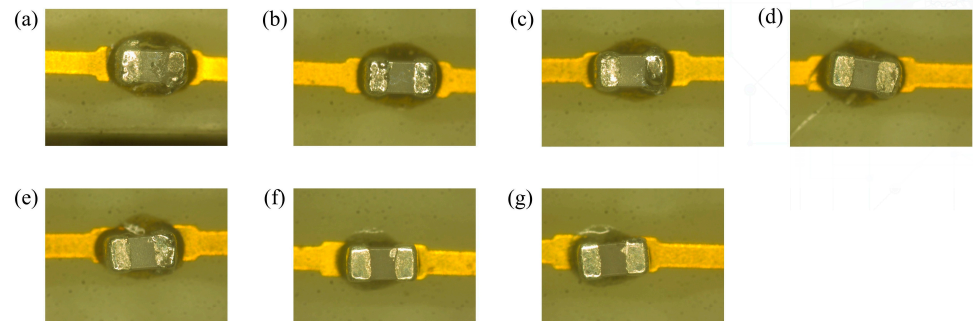


Figure 11. Morphological characterization of chips under different thermocompression tilt angles: (a) 0°; (b) 2°; (c) 4°; (d) 6°; (e) 8°; (f) 10°; (g) 12°.

As the thermocompression tilt angle further increases, particularly at 6° and above, the chip displacement increases markedly and is accompanied by pronounced tangential sliding, leading to a significant degradation in placement consistency. These results suggest that an increasing tilt angle alters the distribution of normal and tangential forces at the bonding interface. While maintaining the normal compressive load, a non-negligible tangential force component is introduced, which promotes chip sliding. Once the tilt angle exceeds a critical threshold (approximately 6°), the tangential effect becomes dominant, resulting in reduced interfacial bonding stability and an increased risk of packaging failure.

The observed experimental phenomena are in good agreement with the predicted effects of pressure inclination obtained from the finite element simulations presented earlier, thereby experimentally validating the proposed simulation model and the associated mechanistic analysis.

As shown in Figure 12b, the thermocompression tilt angle has a pronounced effect on the bonding strength of the chip–ACA interface. With increasing tilt angle, the maximum push–pull force decreases monotonically, indicating a continuous degradation of interfacial adhesion. When the tilt angle increases from 0° to 12° , the maximum push–pull force drops from 4.4 N to approximately 1.2 N, demonstrating a substantial reduction in interfacial bonding strength. Once the tilt angle exceeds 10° , the push–pull force falls to a critical level, at which chip detachment is likely to occur and the structural stability of the package is severely compromised. This behavior suggests that increasing tilt angle alters the distribution of normal pressure and tangential forces at the interface during thermocompression, leading to a significant increase in interfacial shear stress and, consequently, chip sliding.

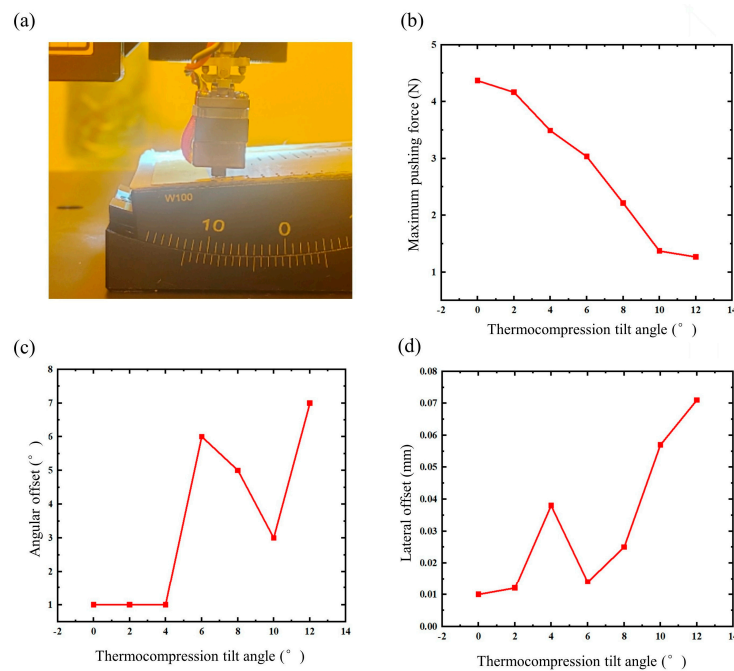


Figure 12. Performance evaluation of thermocompression-bonded samples: (a) Schematic of the thermocompression process; (b) Pull-off force under different tilt angles; (c) Angular misalignment induced at different tilt angles; (d) Lateral displacement induced at different tilt angles.

As illustrated in Figure 12c,d, variations in the thermocompression tilt angle markedly affect both the angular offset and the tangential sliding behavior of the chip. When the tilt angle increases from 0° to 6° , the angular offset rises significantly while tangential sliding remains limited, indicating that chip displacement in this range is primarily governed by angular misalignment. As the tilt angle further increases to 10° , the angular offset decreases, whereas tangential sliding increases rapidly, suggesting that under larger tilt angles, tangential sliding becomes the dominant factor controlling the overall chip displacement and partially compensates for the angular offset. When the tilt angle reaches 12° , both the angular offset and tangential sliding attain their maximum values, and the interfacial bonding state becomes highly unstable, resulting in a substantially increased risk of failure. This behavior is likely associated with the coupled effects of enhanced interfacial shear stress and reduced adhesive strength of the conductive adhesive layer.

Overall, the experimental results are in excellent agreement with the trends predicted by the finite element simulations presented earlier. To ensure reliable bonding between the chip and the pad, it is therefore essential to properly control the thermocompression tilt angle. The experimental data indicate that once the tilt angle exceeds 6° , chip sliding is significantly aggravated and packaging stability deteriorates markedly. Accordingly, it is recommended that the thermocompression tilt angle be maintained below 6° in curved-

surface mounting processes to effectively suppress chip displacement and interfacial failure, thereby improving the reliability and consistency of the packaged structure. This conclusion provides important experimental guidance for optimizing process parameters in multi-chip synchronous thermocompression packaging under curved conditions.

6. Conclusions

To investigate the effects of surface curvature and process parameters on mounting quality during conformal assembly on irregular curved surfaces, this study adopts a curved-surface thermocompression bonding process. A 0402 packaged chip was selected as the anchor chip, and anisotropic conductive adhesive (ACA) was used as the bonding material. A geometric model comprising the thermocompression head–chip–solder–pad–substrate assembly was established on the ANSYS 19.2 Workbench platform. Thermo–mechanical coupled simulations of the thermocompression process were performed to analyze their influence on curved-surface mounting quality, and the simulation results were further validated experimentally. The main conclusions are summarized as follows:

- During conformal bonding on curved surfaces, the stress acting on the chip pads is predominantly concentrated on the inner side of the curvature. As the substrate curvature radius decreases, the maximum stress increases significantly and the stress distribution becomes increasingly localized. Excessive substrate curvature may not only cause the chip to experience excessive peak stress, potentially leading to mechanical failure, but also exacerbate stress non-uniformity, thereby reducing the effective conductive contact area of the ACA. This degradation adversely affects the reliability and stability of the bonded interconnections.
- When angular misalignment occurs during chip placement, misregistration between the upper and lower pads is introduced, resulting in a reduction in the effective load-bearing area. Consequently, the maximum stress increases and becomes more concentrated at the pad corners. Consistent with the above analyses, angular misalignment accelerates chip damage and reduces the effective conductive area of the ACA, thereby severely degrading the bonding quality.
- In the presence of lateral misalignment during chip placement, misregistration between the upper and lower pads leads to a substantial reduction in the effective contact area. As a result, the maximum stress increases and is asymmetrically distributed across the pads on both sides. However, the overall stress distribution remains relatively uniform, and the contact stability is largely preserved. Therefore, small lateral offsets do not significantly deteriorate the bonding quality.
- When an angular deviation exists in the thermocompression loading direction, no misalignment occurs between the upper and lower pads, and the effective contact area remains unchanged. Consequently, the overall stress magnitude is nearly unaffected, while the stress distribution is altered. The pressure angle deviation induces non-uniform loading on the pads at both sides and generates a tendency for lateral sliding. Although the ACA can suppress sliding to a certain extent, excessive pressure angle deviation may still cause chip displacement or even tilting. Therefore, minor deviations in the thermocompression direction do not significantly impair bonding quality; however, large pressure angle deviations must be avoided, as they may lead to severe misalignment and ultimately result in bonding failure.
- Experimental validation was conducted under various thermocompression tilt angles, and the results show excellent agreement with the trends predicted by the preceding finite element simulations. The experimental data further indicate that when the tilt angle exceeds 6° , chip sliding is significantly intensified and the packaging stability deteriorates markedly. Therefore, it is recommended that the thermocompression tilt

angle be maintained below 6° in curved-surface mounting processes to effectively suppress chip displacement and interfacial failure.

Author Contributions: Conceptualization, S.J. and B.X.; methodology, S.J.; software, L.B.; validation, S.J., L.B. and B.X.; resources, P.Z.; data curation, S.J.; writing—original draft preparation, S.J.; writing—review and editing, P.Z.; supervision, P.Z.; project administration, P.Z.; funding acquisition, B.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Hubei (2024AFB618, 2025AFA003), Natural Science Foundation of Wuhan (Special zone project, 2024040701010038), the Key R&D Program of Hubei Province (2025BAB008).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Malik, M.H.; Grosso, G.; Zangl, H.; Binder, A.; Roshanghias, A. Flip Chip integration of ultra-thinned dies in low-cost flexible printed electronics; the effects of die thickness, encapsulation and conductive adhesives. *Microelectron. Reliab.* **2021**, *123*, 114204. [\[CrossRef\]](#)
2. Huang, Y.; Wu, H.; Xiao, L.; Duan, Y.; Zhu, H.; Bian, J.; Ye, D.; Yin, Z. Assembly and applications of 3D conformal electronics on curvilinear surfaces. *Mater. Horiz.* **2019**, *6*, 642–683. [\[CrossRef\]](#)
3. Wang, C.; He, K.; Li, J.; Chen, X. Conformal electrodes for on-skin digitalization. *SmartMat* **2021**, *2*, 252–262. [\[CrossRef\]](#)
4. Wu, H.; Huang, Y.; Xu, F.; Duan, Y.; Yin, Z. Energy Harvesters for Wearable and Stretchable Electronics: From Flexibility to Stretchability. *Adv. Mater.* **2016**, *28*, 9881–9919. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Chen, J.; Yang, S.; Li, Y.; Huang, Y.; Yin, Z. Active curved surface deforming of flexible conformal electronics by multi-fingered actuator. *Robot. Comput.-Integr. Manuf.* **2020**, *64*, 101942. [\[CrossRef\]](#)
6. Choi, J.; Han, C.; Cho, S.; Kim, K.; Ahn, J.; Del Orbe, D.; Cho, I.; Zhao, Z.-J.; Oh, Y.S.; Hong, H.; et al. Customizable, conformal, and stretchable 3D electronics via predistorted pattern generation and thermoforming. *Sci. Adv.* **2021**, *7*, eabj0694. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Park, J.; Kim, D.; Yoo, C.S.; Lim, T.; Chung, B.-M. Development of Cost-Effective Ni-Less Surface Finishing Process for High-Speed PCBs. *J. Electron. Mater.* **2023**, *52*, 7504–7511. [\[CrossRef\]](#)
8. Straubinger, D.; Koltay, P.; Zengerle, R.; Kartmann, S.; Shu, Z. Versatile Selective Soldering via Molten Metal Printing for Heat-Sensitive 3D Electronics and Smart Wearables. *Adv. Funct. Mater.* **2025**, *35*, 2419653. [\[CrossRef\]](#)
9. Takakuwa, M.; Yamagishi, K.; Lee, S.; Tagawa, Y.; Someya, T.; Yokota, T. Device integration technology for practical flexible electronics systems. *Adv. Funct. Mater.* **2026**, *36*, e14330.
10. Bo, R.; Xu, S.; Yang, Y.; Zhang, Y. Mechanically-guided 3D assembly for architected flexible electronics. *Chem. Rev.* **2023**, *123*, 11137–11189. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Ye, S.; Zhao, P.; Li, S.; Kavousi, F.; Hao, G. Design and Modeling of a Non-Flat Foldable Tubular Kirigami with Compliant Joints. *J. Mech. Robot.* **2024**, *16*, 091005. [\[CrossRef\]](#)
12. Kim, J.; Zhang, Z.; Won, D.; Yoon, S.; Jin, Y. A pick-and-place process control based on the bootstrapping method for quality enhancement in surface mount technology. *Int. J. Adv. Manuf. Technol.* **2024**, *133*, 745–763. [\[CrossRef\]](#)
13. Lall, P.; Zhang, Y.; Miller, S. Reliability Performance Analysis of Magnetically-Oriented ACA for Flexible and Stretchable Electronics. In *Proceedings of the 2024 23rd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*; IEEE: New York, NY, USA, 2024; pp. 1–8.
14. Lall, P.; Sarwar, M.G.; Soni, V.; Miller, S. Performance Evaluation of Direct Write Thermoformed Additively Printed Silver Circuits with Eca for In Mold Electronics. *J. Electron. Packag.* **2026**, *148*, 031007. [\[CrossRef\]](#)
15. Andrew, S.; Teutsch, T.; Azdasht, G.; Giere, M. Laser Based Assembly of Ultra Fine Pitch Bumped ICs for Chip-on-Chip Proximity Coupled Applications. In *Proceedings of the 2009 International Symposium on Microelectronics*; IEEE: New York, NY, USA, 2009; pp. 001032–001038.
16. Lu, S.T.; Lin, Y.M.; Chuang, C.C.; Chen, T.-H.; Chen, W.-H. A novel compliant-bump structure for ACA-bonded chip-on-flex (COF) interconnects with ultra-fine pitch. In *Proceedings of the 2009 59th Electronic Components and Technology Conference*; IEEE: New York, NY, USA, 2009; pp. 1544–1551.
17. Ozeki, H.; Tsukao, R.; Shin, Y. Enabling Next-Generation MicroLED Displays Through ACF-Based Bonding Solutions. *Inf. Disp.* **2025**, *41*, 12–16. [\[CrossRef\]](#)

18. Huynh, V.L.; Aasmundtveit, K.E.; Nguyen, H.V. Enabling low pressure, low temperature, and particle control for anisotropic conductive adhesives. *Adv. Mater. Technol.* **2024**, *9*, 2400262. [[CrossRef](#)]
19. Gao, L.; Gao, H.; Chen, X. Recent advances in mechanical properties of anisotropic conductive adhesive film for microelectronic packaging. *Solder. Surf. Mt. Technol.* **2015**, *27*, 164–177. [[CrossRef](#)]
20. Lall, P.; Sarwar, M.G.; Soni, V.; Miller, S. Direct Write Thermoformed Additive Silver Circuits with SMDs Attachment for In-Mold Electronics. In *International Electronic Packaging Technical Conference and Exhibition*; American Society of Mechanical Engineers: New York, NY, USA, 2023; Volume 87516, p. V001T03A016.
21. Hilbich, D.D. A New, Low-Cost, PDMS Metallization Process for Highly Conductive Flexible and Stretchable Electronics. Ph.D. Thesis, Simon Fraser University, Burnaby, BC, Canada, 2017.
22. Sharma, A. *Transfer Printing of Stretchable Electronic Circuits on Conformal Surfaces*; State University of New York at Buffalo: Buffalo, NY, USA, 2015.
23. Gee, N.D. *Electromechanical Characterization of Printed Interconnects for Die Attach on Flexible Substrates and Liquid Metal Ink on Stretchable Substrates*; State University of New York at Binghamton: Binghamton, NY, USA, 2023.
24. Lau, C.S.; Abdullah, M.Z.; Che, A.F. Computational fluid dynamic and thermal analysis for BGA assembly during forced convection reflow soldering process. *Solder. Surf. Mt. Technol.* **2012**, *24*, 77–91. [[CrossRef](#)]
25. Chiang, K.N.; Chang, C.W.; Lin, C.T. Process Modeling and Thermal/Mechanical Behavior of ACA/ACF Type Flip-Chip Packages. *J. Electron. Packag.* **2001**, *123*, 331–337. [[CrossRef](#)]
26. Hwang, H.; Kong, M.; Kim, K.; Park, D.; Lee, S.; Park, S.; Song, H.-J.; Jeong, U. Stretchable anisotropic conductive film (S-ACF) for electrical interfacing in high-resolution stretchable circuits. *Sci. Adv.* **2021**, *7*, eabh0171. [[CrossRef](#)] [[PubMed](#)]
27. Aradhana, R.; Mohanty, S.; Nayak, S.K. A review on epoxy-based electrically conductive adhesives. *Int. J. Adhes. Adhes.* **2020**, *99*, 102596. [[CrossRef](#)]
28. Zhang, H.; He, Q.; Yu, H.; Qin, M.; Feng, Y.; Feng, W. A Bioinspired Polymer-Based Composite Displaying Both Strong Adhesion and Anisotropic Thermal Conductivity. *Adv. Funct. Mater.* **2023**, *33*, 2211985. [[CrossRef](#)]
29. Lin, Y.C.; Zhong, J. A review of the influencing factors on anisotropic conductive adhesives joining technology in electrical applications. *J. Mater. Sci.* **2008**, *43*, 3072–3093. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.