ASSESSING THERMAL DEFORMATION RISKS IN ELECTRONIC REPAIRS: BRIDGING SIMULATION GAPS FOR ENHANCED RELIABILITY

Kevin Boissie – Valeo, Circular Electronic Laboratory, Nevers, France
Alireza Morsali – Valeo Brain, Créteil, France
Sofiane Saad – Valeo Brain, Créteil, France
Noah Gagnon – Valeo Brain, Troy, USA
Fabrice Blasenhauer – Valeo SC2N, Mondeville, France
Jean-Baptiste Prono – Valeo Brain, Créteil, France

Abstract

The rapid evolution of electronics repair methodologies, especially in industrial and batch processing contexts, necessitates a thorough understanding of thermomechanical stress and its associated mechanical deformations. Rework operations, whether conducted manually or through automation, combined with the materials and structural design of the components, lead to uneven temperature distribution across the component. Conventional simulations typically assess the heating effects across entire components, overlooking the localized thermal stresses encountered during specific rework or repair interventions. This limitation may lead to underestimations of mechanical strain and thermal propagation, potentially undermining the long-term reliability of repaired electronic components.
The study, carried out by Valeo's Circular Economy Laboratory, addresses this gap by exploring differential outcomes between global heating simulations and localized thermal analyses during repair processes. Through a series of controlled experiments and simulation techniques, critical discrepancies in thermal stress distribution during isolated repair procedures were identified. Key findings indicate that localized heating generates non-uniform thermal gradients and mechanical deformations, aspects often overlooked by existing simulation models, posing potential risks to the structural integrity of components post-repair.
To enhance predictive accuracy, a protocol was developed and validated, incorporating a simulation framework that takes account of localized thermal profiles and their mechanical impacts. This framework enables precise identification of heat-sensitive zones, facilitating targeted thermal management strategies and adaptation of repair parameters. Such improvements are essential for maintaining the mechanical properties and performance of components after rework, thereby aligning with sustainability and circular economy principles by extending the operational lifespan of electronic components.
The implications of this research are significant for both industry and academia. By providing a more accurate method for thermal-induced deformation risk evaluation during electronic repairs, tools are offered to manufacture and repair to address reliability concerns. Additionally, this work opens avenues for the further refinement of simulation tools and methods that align with the practical demands of electronic repair, thereby, supporting product longevity and resource efficiency—a core tenet of the circular economy.
The findings presented not only highlight current limitations but also propose a practical approach that can be integrated into standard repair protocols or simulation practices. This innovation underscores the importance of revisiting traditional modeling assumptions in light of real-world repair conditions to foster sustainable manufacturing practices and align with energy and environmental goals.

Introduction and Motivation

The automotive sector plays a pivotal role in climate change mitigation, guided by ambitious global greenhouse gas reduction targets. The European Union, for instance, aims to reduce emissions by 55% by 2030 compared to 1990 levels, progressing toward full climate neutrality by 2050 [1]. France has also outlined a strategy to halve its emissions by 2030, signaling a unified commitment to achieving environmental sustainability [2]. These initiatives underscore the urgency of adopting innovative solutions across industries, with the automotive sector playing a pivotal role. Electronics are essential for achieving these goals. In particular, automotive electronic systems contribute to CO_2 reduction through enhanced energy efficiency, optimized vehicle performance, and the facilitation of electric and hybrid powertrains. A recent study found that improving energy management in power electronics and thermal control systems can reduce overall vehicle emissions by up to 5-10%, particularly in hybrid and electric powertrains [3].

Electric vehicles (EVs), which produce substantially fewer lifecycle emissions than internal combustion engine vehicles, exemplify the sector's progress [3]. However, the role of electronics extends beyond EVs. Innovations in autonomous driving, infotainment, connectivity, and advanced safety systems have significantly increased the share of electronics in modern vehicles. For instance, the electronic content in vehicles has grown from 10% of the total vehicle cost in the 1970s to over 35% today, and it is expected to exceed 50% for premium models by 2030 [4]. These systems not only enhance user experience and safety but also contribute to the complexity and cost of vehicle electronics. The adoption of EVs and advanced technologies, while promising, presents significant economic challenges. These include the high cost of critical components such as power control units, batteries, and sensors, as well as the maintenance of intricate electronic systems. Cost-efficient repair strategies are essential for overcoming these challenges, ensuring the long-term sustainability of advanced automotive systems. Recent lifecycle assessments indicate that extending the operational lifespan of automotive electronics by five years through repair and refurbishment can lower total lifecycle emissions by approximately 15-20%, primarily by reducing the need for new component manufacturing [5]. As the electronics within vehicles become increasingly complex, reparability must be embedded in the design process. Traditional practices often prioritize performance and compactness over ease of maintenance, leading to increased waste and higher replacement costs. In contrast, designing components with reparability in mind can extend their operational lifespan and reduce environmental impact, aligning with circular economy principles.

Reparability hinges on several key factors, including material selection, modularity, and accessibility. For example, employing durable materials that withstand thermal and mechanical stress during repair processes can prevent component failure. Modularity allows for the replacement of individual subcomponents rather than entire assemblies, lowering costs and waste. Accessibility ensures that repair operations can be performed efficiently, even for intricate electronic assemblies. Establishing robust design rules that address these factors is critical for enabling sustainable repair practices.

Thermal management is particularly important in the context of electronic repairs. During rework or repair operations, localized heating can cause non-uniform thermal gradients, leading to mechanical deformations that compromise the structural integrity of components. Conventional simulation methods often fail to capture these localized effects, focusing instead on global temperature distributions. This gap in predictive capability can result in unexpected failures and reduced reliability post-repair. Addressing these limitations requires the development of advanced simulation frameworks that account for the unique thermal and mechanical dynamics of repair processes.

The work presented in this study seeks to bridge this gap by introducing a simulation framework that accurately evaluates localized thermal stresses during electronic repairs. By identifying heat-sensitive zones and assessing their impact on mechanical deformation, the proposed approach enables targeted thermal management strategies. These strategies not only enhance the reliability of repaired components but also support the broader objectives of sustainability and cost efficiency in the automotive sector.

In conclusion, the automotive industry faces dual pressures to meet environmental goals and reduce costs associated with advanced electronic systems. By prioritizing reparability and leveraging advanced simulation tools, the sector can address these challenges effectively. This work highlights the importance of revisiting traditional design and simulation assumptions to foster sustainable manufacturing practices, extend the lifecycle of critical components, and align with global climate objectives.

Current State of the Technology Industry Uses

The advancement of automotive electronics has introduced new challenges in thermal management, simulation techniques, and the design for reparability. These challenges require addressing thermomechanical stresses, enhancing reliability, and incorporating sustainability principles into industrial practices. This section reviews relevant studies and industrial developments, organized into thematic subsections.

Advanced Thermal Management Techniques

Efficient thermal management is a cornerstone for ensuring the reliability and performance of modern electronic systems. Studies have shown that inadequate thermal management can reduce component lifespan by over 50%, emphasizing the need for optimized heat dissipation strategies [6]. Traditional approaches, which often rely on global thermal profiles, fail to capture localized heating effects during repair operations. Recent advancements have focused on thermal interface materials (TIMs) that demonstrate up to 30% better heat transfer efficiency compared to conventional solutions [7]. Additionally, liquid cooling systems, particularly those integrated with micro-channels, have proven to improve thermal performance by 40% in high-power applications [8]. Graphene-enhanced TIMs further enhance thermal conductivity by up to 60%, representing a breakthrough in material science for electronic cooling [9]. The use of predictive thermal management systems leveraging artificial intelligence has also gained traction, enabling real-time adjustments to improve energy efficiency by 20% [10]. A recent innovation is the integration of phase-change materials in electronic systems, enhancing thermal regulation by up to 50%, which is particularly relevant for high-density power applications [11]. Moreover, the application of nano-fluids in cooling systems has shown promising results, enhancing heat transfer rates by 30% compared to traditional coolants [12].

Simulation Techniques for Thermomechanical Reliability

Simulation tools play an indispensable role in addressing thermomechanical challenges. Finite Element Method (FEM) simulations combined with machine learning algorithms have demonstrated a 30% increase in predictive accuracy for thermal stress distributions [13]. Digital twin technology, which replicates physical systems virtually, has significantly enhanced component reliability assessments under variable conditions, reducing failure rates by 40% [14]. Hybrid simulation approaches that integrate experimental data with numerical models have facilitated more accurate predictions of failure mechanisms. For example, coupling thermal simulations with structural analyses allows engineers to identify critical stress points, reducing development times by 25% [15]. A recent breakthrough in this domain includes the use of quantum computing algorithms to simulate thermal and mechanical stresses with unparalleled precision, enabling a 50% reduction in computation times for large-scale simulations [16].

Design for Reparability in Electronics

Reparability is emerging as a critical consideration in the design of electronic systems. Legislative measures such as the European Union’s "Right to Repair" directive have spurred manufacturers to develop products with modular architectures, making repairs easier and more cost-effective [17]. Modular designs have been shown to reduce repair times by 50%, while also enabling the replacement of subcomponents rather than entire assemblies [18]. Recent innovations include augmented reality (AR) repair assistance tools, which improve repair precision and reduce error rates by 35% [19]. Such technologies enhance the accessibility and efficiency of repair operations, particularly for intricate electronic assemblies. Additionally, reparability-scoring systems have been standardized to compare the ease of repair across different products. Devices scoring higher on these indices exhibit a 30% longer operational lifespan, aligning with circular economy principles [20]. The use of biodegradable electronic materials is also being explored to facilitate easier disassembly and repair, reducing environmental impacts significantly. Pilot studies have shown that such materials can lower the ecological footprint of electronic repairs by 25% [21].

Industrial Practices and Sustainability Strategies

Sustainability has become a central theme in the technology industry, driving the adoption of practices that minimize environmental impact. Comprehensive sustainability assessments now encompass the entire lifecycle of electronic products, from material extraction to end-of-life recycling. For instance, the implementation of circular economy principles has increased material reuse rates by 25% [5]. The integration of block chain technology into supply chain management has improved transparency and compliance with environmental regulations, enhancing supplier adherence by 30% [22]. In addition, innovations in carbon capture and storage technologies have contributed to a 15% reduction in greenhouse gas emissions in industrial processes [23]. Energy efficiency improvements in manufacturing processes, enabled by smart monitoring systems, have led to a 20% reduction in energy consumption [24]. These efforts not only address environmental challenges but also provide significant cost savings, underscoring the economic viability of sustainable practices. Recent advancements in green manufacturing technologies, such as additive manufacturing using recycled materials, have further reduced energy consumption and material waste by 40% [25].

Technology Approach

Addressing the challenges of localized thermal stress during rework operations requires a comprehensive methodology that combines experimental measurements and advanced simulation techniques. Conventional simulation frameworks, while effective for global heating scenarios, often fall short in capturing the non-uniform thermal gradients and mechanical deformations induced by rework processes. To bridge this gap, we developed an approach that integrates experimental validation with a refined simulation framework tailored to the specific conditions encountered during localized heating.

This section outlines the strategies employed to characterize and model the thermal and mechanical dynamics of PCB rework operations. The experimental setup was designed to measure the temperature propagation and gradients with high spatial and temporal resolution, providing critical insights into the thermal stress distribution. These results guided the development of a simulation framework that accurately replicates localized effects during rework, improving risk prediction.

By combining experimental data with advanced modeling techniques, this approach provides a foundation for improving thermal management strategies and enhancing the reliability of electronic components subjected to repair operations.

Thermal Profiles in SMT Production vs. Rework Operations: Implications for PCB Stress

The thermal management strategies employed during SMT (Surface Mount Technology) production and rework operations differ significantly in terms of both temperature profiles and exposure durations. These differences lead to distinct thermal stress distributions that impact the reliability of PCBs (Printed Circuit Boards).

For SAC305 (Sn96.5Ag3Cu0.5) solder alloy, these variations in temperature application are particularly relevant. SAC305 is widely used in the electronics industry due to its compliance with RoHS (Restriction of Hazardous Substances) regulations and its favorable combination of thermal and mechanical properties, making it a standard reference for soldering applications. Its melting point of 217°C and well-documented thermal behavior provide a reliable basis for analyzing the effects of thermal profiles during both production and rework processes.

During SMT production, the PCB undergoes a well-defined thermal cycle in a reflow oven. The temperature profile is carefully controlled to ensure uniform heating and minimize thermal gradients. The process begins with a preheating phase, where the PCB temperature is gradually increased to 150–180°C over 60–120 seconds, preventing thermal shock. This is followed by a soaking phase at 180–200°C for 60–90 seconds, which homogenizes the temperature across the board. In the reflow phase, the temperature peaks between 230–245°C, slightly above the alloy's melting point of 217°C, for 30–60 seconds to achieve optimal solder joint formation. Finally, the cooling phase proceeds at a controlled rate of 2–4°C per second, reducing the risk of mechanical stress due to abrupt temperature changes.

In contrast, rework operations apply highly localized and rapid heating, often using hot air or infrared rework stations. The targeted zone is heated to 260–280°C for 15–30 seconds, far exceeding the peak temperatures used during SMT production. Localized heating creates steep thermal gradients, with temperature variations between the heated zone and surrounding areas reaching 50–100°C. These gradients create significant mechanical stresses, which may lead to micro-cracks in solder joints or delamination of PCB layers. Additionally, the prolonged exposure of 60–90 seconds at elevated temperatures, including time for manipulation of components, further exacerbates these risks. Unlike SMT production, cooling during rework is often uncontrolled, resulting in uneven thermal contraction and increased susceptibility to damage.

Limitations of Current Simulation Models

Despite the critical importance of thermal management, conventional simulation tools used in PCB design primarily focus on global thermal effects during production, often neglecting localized heating scenarios encountered in rework. Existing models do not adequately account for the sharp thermal propagation gradients and non-uniform stress distributions inherent to rework operations. This limitation can lead to inaccurate predictions of mechanical deformation; solder joint integrity, and the long-term reliability of repaired components. Experimental validation is essential to address these gaps. Key parameters such as localized temperature distribution, thermal propagation rates, and resulting mechanical stresses must be measured directly to refine simulation frameworks. Accurate experimental data enables the development of predictive models that better represent real-world repair conditions.

Methodology for Measuring Temperature Propagation during Rework

To evaluate thermal propagation during rework operations, an experimental setup was developed to capture localized temperature profiles on a PCB subjected to rework-like conditions. The experimental procedure included the following steps:

1. Sample Preparation: PCBs with SAC305 solder joints were instrumented with high-precision thermocouples placed at multiple locations, including the heated zone, adjacent areas, and the PCB's edges. This configuration allowed for real-time monitoring of temperature gradients.
2. Rework Simulation: A hot air rework station was used to apply localized heating to a specific component on the PCB. The heating temperature was set to 260–280°C, with a ramp-up time of approximately 15 seconds, simulating typical rework conditions. The selected temperature range aligns with industry standards for rework processes and is based on prior studies demonstrating effective component desoldering without excessive thermal stress.
3. Data Acquisition: Temperatures were recorded continuously at a sampling rate of 10 Hz using a data acquisition system. Infrared cameras were also employed to capture thermal images, providing spatially resolved temperature data across the PCB surface.
4. Analysis of Thermal Gradients: The recorded data was analyzed to determine the rate of temperature propagation, the maximum temperature gradients, and the duration for which the thermal stress persisted in different regions of the PCB. Experimental trials were conducted multiple times under identical conditions, yielding consistent results with minimal deviation, confirming the repeatability of observed thermal gradients.
5. Validation with Simulation: Experimental results were compared with predictions from finite element simulations, highlighting discrepancies between simulated and measured thermal gradients and enabling calibration of the model.

The electronic rework station with the overview of tools and operation are shown in Figure 1.

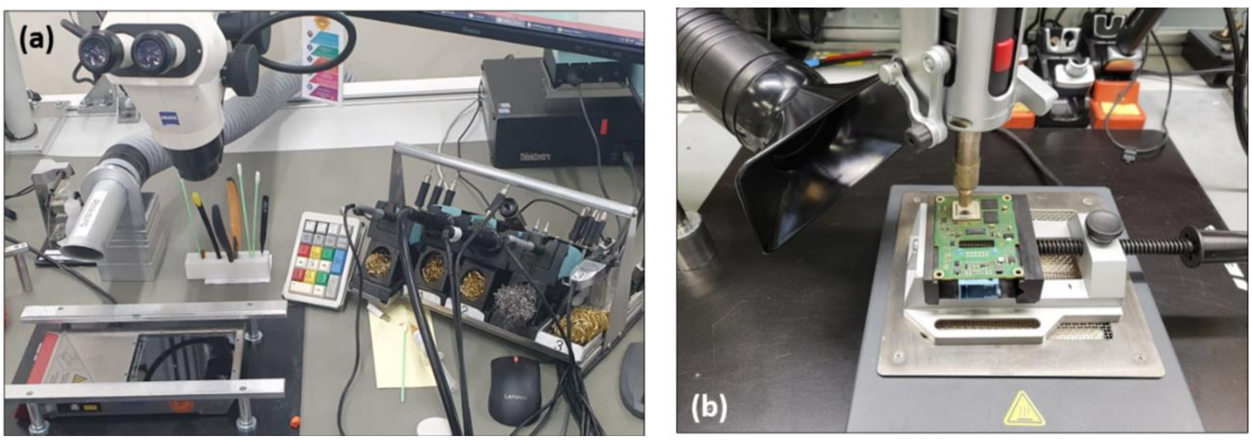

Figure 1. Electronic Rework Station
(a) Overview of tools, (b) Rework operation

Discussion

The findings presented in this study highlight the significant differences between global and localized heating effects during electronic rework. While conventional simulation methods provide reliable assessments for uniform heating scenarios, they often fail to capture the sharp thermal gradients and stress concentrations induced by localized heating. This discrepancy can lead to underestimations of mechanical deformations and potential failure risks in repaired components. By integrating experimental validation with refined simulation models, this work demonstrates the necessity of incorporating localized thermal effects into predictive frameworks. For example, optimization of thermal shielding during repair has been shown to prevent PCB delamination in high-density ECU boards, a frequent failure mode observed in field returns [26]. The following sections present the key experimental observations and numerical simulations that support these conclusions.

Experimental Results

The printed circuit board assembly (PCBA) depicted in Figure 1 (b) was subjected to two distinct thermal processes: an initial complete heating cycle in a reflow oven and a subsequent localized heating procedure using a hot air flow machine, specifically targeting a single system-on-chip (SoC) component. The resulting temperature distribution across the PCBA was measured using an infrared camera. The corresponding temperature measurement data are presented in Figure 2.

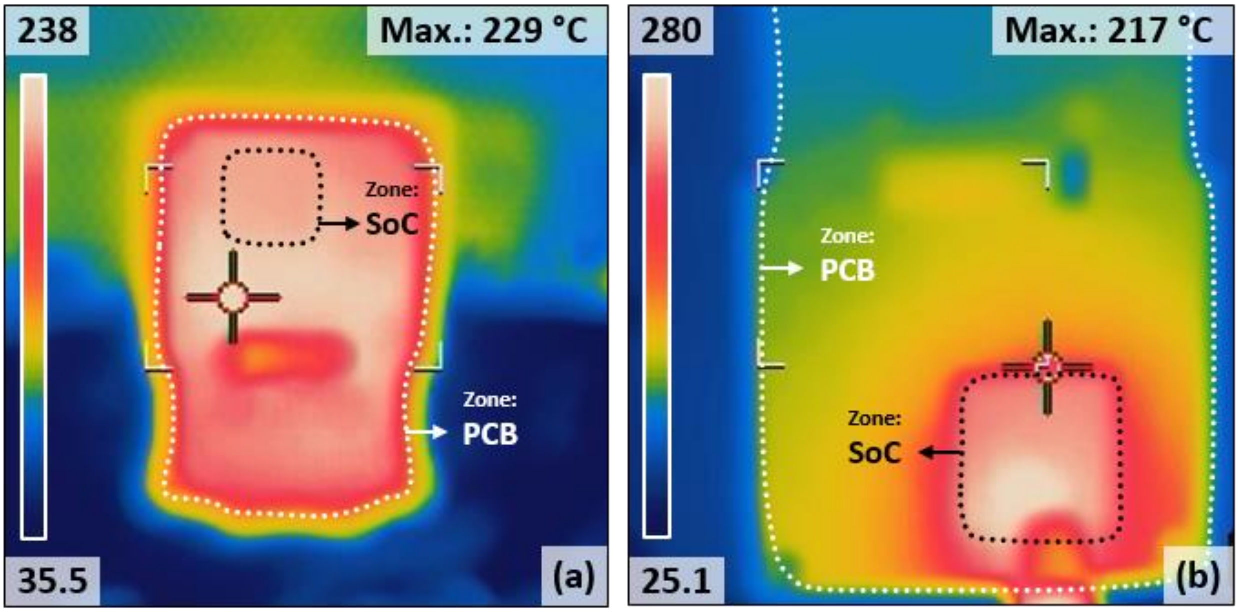

Figure 2. Temperature Distribution Across the PCBA Under Different Heating Methods
(a) Temperature Distribution After Full Reflow Oven Heating
(b) Temperature Distribution After Localized Heating with Hot Air Flow Machine

The PCBA exhibits distinct heating characteristics under the two methods. In reflow oven heating shown in Figure 2 (a), the entire PCBA is uniformly heated. However, a slightly lower temperature is observed around the SoC and its neighboring memory modules. This is probably due to the higher thermal absorption by the SoC and adjacent components, which act as a mask over the underlying PCB. Since the primary heat source in the oven targets the top surface, this shielding effect results in reduced heating of the PCB in those areas.
The metallic EMI shield of the SoC, reflective to infrared radiation, also causes the infrared camera to underestimate the actual temperature of the SoC. This effect should be considered when interpreting the results.
In localized heating using a hot air flow machine shown in Figure 2 (b), the temperature is concentrated around the SoC and the components on the same side of the PCBA. In contrast, oven heating results in a slightly higher temperature on the PCB's opposite side. These results highlight the difference between global and targeted heating methods.

Simulation Results

A simplified 3D model of the PCBA, shown in Figure 3 (a), was used to simulate heat transfer, thermal stress, and the resulting warpage and deformation. The 3D model and the simulation results for heat transfer in the PCBA, using both global and localized heating methods, are presented in Figure 3.

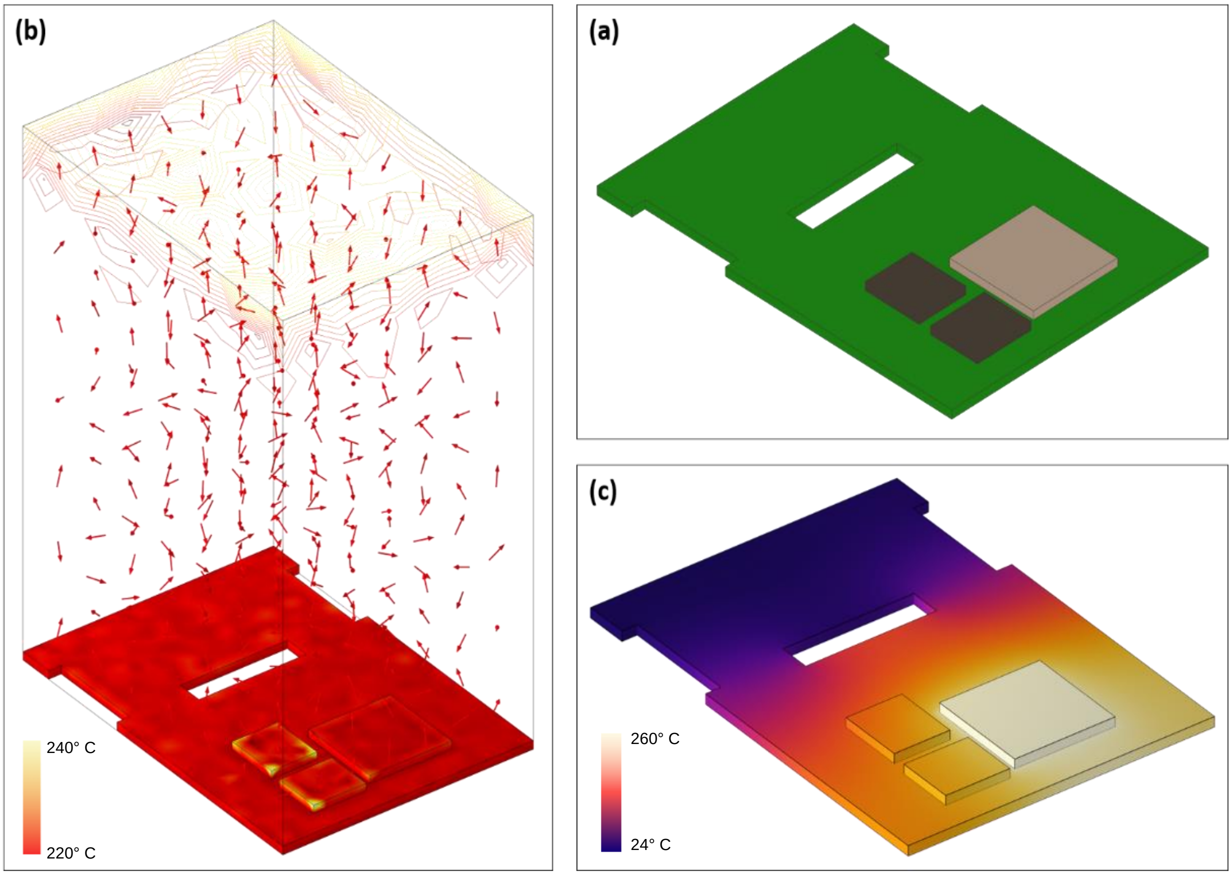

Figure 3. 3D Model and Heat Transfer Simulation of the PCBA
(a) Simplified 3D Model of the PCBA
(b) Heat Transfer Simulation: Reflow Oven Heating
(c) Heat Transfer Simulation: Localized Heating with Hot Air Flow Machine

As shown in Figure 3 (a), the SoC and neighboring memory components are included in the simplified 3D model of the PCBA. This decision was made based on observations from Figure 2 (a), which indicate these components can potentially influence heat transfer to the underlying.

In the oven case, as seen in Figure 3 (b), heat transfer results in a relatively uniform temperature distribution across the PCB. In the localized heating scenario shown in Figure 3 (c), where only the SoC is heated, the temperature is concentrated around the SoC and the side of the PCB where the SoC and memory components are located. These results demonstrate strong agreement between the experimental and simulation data, validating the model's accuracy in capturing the thermal behavior of the system.

The rise in temperature of the PCBA induces thermal stress and deformation, which were also simulated. Simulation parameters, including oven and hot air flow temperatures, were matched with experimental conditions to ensure consistency. Since experimental measurement of deformation and thermal stress is more complex than temperature measurement using an infrared (IR) camera, the correlation between the simulated and experimental temperature distributions serves as a basis for validation. This correlation suggests that the simulated results for deformation and thermal stress closely resemble practical behavior, making them highly reliable. The simulation results for deformation and thermal stress are presented in Figure 4.

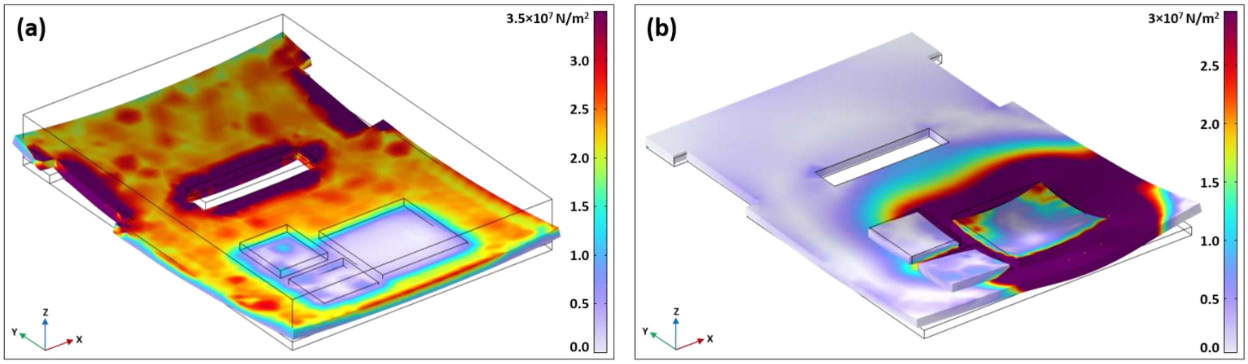

Figure 4. Simulation Results for Thermal Stress and Deformation in the PCBA
(a) Thermal Stress and Deformation: Reflow Oven Heating
(b) Thermal Stress and Deformation: Localized Heating with Hot Air Flow

It was seen in Figure 3 (a), the PCB includes a central aperture and a symmetrical neck, defined by a latitudinal reduction in width along the longitudinal axis. It is observable in Figure 4 (a), representing the oven case, the thermal stress is nearly uniform across the entire structure, accompanied by even deformation throughout the PCB. Notably, the thermal stress is lower around and beneath the components on the PCB, while higher values are observed in the neck and around the central aperture.

In contrast, for the hot air flow case—Figure 4 (b), there is a significant concentration of thermal stress beneath and particularly around the SoC, where the nozzle of the hot air flow machine was positioned during heating. Unlike the oven case, this results in uneven deformation, manifesting as warpage in the PCB.

The uniform thermal stress and even deformation in the oven case shown in Figure 4 (a) and the concentrated thermal stress and warpage in the hot air flow case—Figure 4 (b), follow a pattern consistent with the temperature distribution observed in the experiments (Figure 2) and the heat transfer behavior simulated in Figure 3.

It should be noted that the deformation depicted in the figures has been scaled up by a factor of 50 for better visual detectability.

The key numerical results of the simulation, including the thermal stress and the displacement in three axes at the center of the area of the PCB covered by the SoC (located on the top side), with values corresponding to the bottom side, are detailed in Table 1.

Table 1. Key Numerical Results of Thermal Stress and PCB Displacement from Simulation

Heating system	Thermal Stress (N/m^2)	XYZ-Axes Displacements (μm)		
Oven	3.07×10^6	31.25	14.89	-56.75×10^{-3}
Hot Air Flow	21.72×10^6	33.55	14.55	-3.81

Conclusions & Recommendations

This study provides a comprehensive assessment of thermal deformation risks in electronic rework processes, focusing on the impact of localized heating on PCB mechanical integrity. Experimental and simulation results reveal that localized heating induces significantly higher thermal stress and warpage compared to global reflow heating, with stress levels and Z-axis displacements approximately 7.1 and 6.7 times greater, respectively.

These findings highlight the need to revise repair methodologies and simulation approaches to improve the reliability and sustainability of electronic repairs. Conventional thermal stress simulation routines, primarily designed for manufacturing conditions with global heating, do not fully account for localized heating effects commonly encountered in rework processes. Incorporating these effects is essential for a more accurate assessment of repair-induced deformations. For example, thermal aging during the rework process could reduce the lifespan of solder joints. Internal measurements at Valeo indicate that for a specific PCB, the coefficient of thermal expansion (CTE) increased from 19.6 to 20.4 ppm/°C after exposure to a 105°C temperature amplitude for 1.5 hours. Therefore, it is essential to incorporate the reduction in solder joint lifespan and the evolving CTE of PCBs into the simulations. Enhancing the accuracy of CTE mismatch predictions is crucial for improving the reliability and longevity of solder joints [26].

Mapping the relationship between solder joint lifespan and post-rework PCB CTE using CFD thermal simulations will contribute to increasing the confidence level and maturity of the assessments.
Experimental approaches play an equally important role in understanding potential repair-induced degradation. Preliminary investigations indicate that localized rework heating exceeding 280°C for prolonged durations can lead to microcracking in SAC305 solder joints, though further systematic testing is required to quantify defect initiation thresholds. Similarly, high-temperature ramp rates above 10°C/sec have been linked to PCB delamination in high-layer count assemblies [27]. Future work should focus on developing standardized testing methodologies to quantify microcrack formation in reworked electronic assemblies, potentially integrating in-situ acoustic emission techniques for early defect detection.
From an industrial standpoint, standardizing repair protocols and simulation practices is essential to enhancing the reliability of electronic components across diverse manufacturing environments. Establishing guidelines to account for localized heating effects, defining stress thresholds, and refining model calibration through experimental validation will improve predictive accuracy and reduce failure rates in reworked assemblies. Developing industry-wide databases on thermal stress behaviors under rework conditions would further support precise simulations and informed decision-making during repairs. For instance, our simulations indicate that solder joint reliability is compromised when localized stress levels exceed 18 MPa, aligning with empirical fatigue thresholds reported in prior studies [26]. Additionally, PCB warpage beyond 150 µm in reworked assemblies has been correlated with high failure rates in automotive applications, suggesting an upper design limit for acceptable deformation [27].
To address these challenges, repair processes should incorporate targeted thermal management strategies, such as controlled preheating, optimized heat shielding, and localized temperature regulation. Encouraging modular component design can also facilitate reparability while minimizing stress accumulation during repair operations.
Future research should extend beyond thermal-induced deformation to include other contributing factors, such as mechanical vibrations, humidity exposure, and repeated rework cycles, to develop a comprehensive understanding of repair-induced stresses. A promising avenue is the use of AI-driven predictive models that leverage machine learning algorithms to correlate historical repair data with field failure rates, thereby enabling proactive failure mitigation strategies. Additionally, advancements in real-time thermal monitoring during rework could facilitate adaptive control systems, reducing excessive thermal exposure and ensuring consistent repair quality [10]. Advancements in AI-driven predictive models and real-time thermal monitoring could further enhance simulation accuracy and improve repair reliability.
Moreover, integrating these approaches into broader lifecycle assessments will support circular economy initiatives by promoting sustainable electronic design and extending product lifespans.
By addressing these aspects, this study contributes to the advancement of electronic repair methodologies, reducing waste and enhancing the long-term reliability of critical electronic systems.

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About the Authors

Dr. Kevin Boissié, Circular Electronic Laboratory Leader, Senior Expert in Obsolescence Engineering, Vice Chair at International Institute of Obsolescence Management. Working in Valeo Brain, in Nevers, France since 2005.
Dr. Alireza Morsali, R&I Product Leader at Valeo Brain, Créteil, France, Ph.D. in Microelectronics and Photonics, working at Valeo since 2023 on circular microelectronics and optoelectronics.
Dr. Sofiane Saad, Expert in FEA Simulation and Electronic Reliability. Working in Valeo Brain, Créteil, France since 2017.
Noah Gagnon – Valeo Brain, MI Troy, USA, Electronics Lead for Valeo Troy Site. Working in Valeo since 2010 specializing in electronic module design including ADAS Compute, Vision, and Ultrasonic controllers.
Fabrice Blasenhauer, Expert in reliability, Reliability & NVH Manager at Valeo SC2N, Mondeville, France. Working in Valeo, since 2010
Jean-Baptiste Prono – Valeo Brain, Créteil, France, R&D Circular Economy program manager, working in Valeo since 5 years