

CASE STUDY

Measuring Thermal Expansion Anisotropy in Printed Circuit Boards with Thermomechanical Analysis

How PCBs Expand When Heated

Every material expands when heated, but a printed circuit board (PCB) is not one material; it's a stack of very different ones bonded together: copper traces and planes, glass-reinforced epoxy laminate (the insulating base material of the board), solder, and mounted components, each with its own coefficient of thermal expansion (CTE). When a board heats up or cools down, these layers don't move by the same amount, and that mismatch is a major cause of failure in electronic assemblies.¹

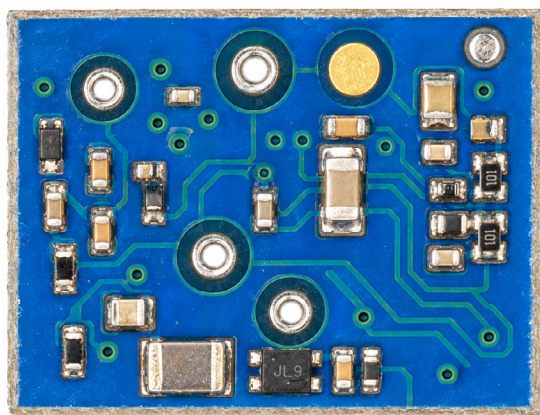


Figure 1: Photo of the PCB used for this study.

Why the Industry Cares

CTE mismatch isn't a niche concern confined to a single product category. It shows up wherever a board has to survive real-world temperature swings without an isolated, tightly controlled thermal environment protecting it, which in practice covers most of electronics manufacturing. Automotive and aerospace electronics make the case most sharply, because they combine wide temperature ranges with almost no tolerance for the board flexing to accommodate that mismatch on its own. AI data center hardware arrives at the same problem from the opposite direction: the room is climate controlled, but the power moving through the board is not steady.

Automotive electronics are the clearest case of CTE mismatch causing problems. Boards are mounted in tight, harsh under-hood locations that see roughly -40°C to $+125^{\circ}\text{C}$ for standard automotive-qualified electronics², and they are rigidly attached at every joint, so each excursion across that range is absorbed as mechanical strain rather than free movement.

Aerospace and defense push the same problem further. These sectors demand near-zero failure rates under extreme temperature variation.³ Weight reduction requirements push designs toward high-density interconnect and rigid-

flex construction that pack more circuitry into less volume. Tighter packaging combined with a wider thermal range makes CTE mismatch worse, not better, which is why aerospace-grade boards often specify low-CTE materials, specifically to keep the board's expansion closer to the copper and other components it's mated to.

AI data center hardware is the newest case, and it undercuts the assumption that a climate-controlled facility means a well-controlled thermal environment in the boards themselves. In an AI data center, what heats the board is the internal work it is doing, not the weather outside. A rack of GPUs running a training job all step through different parts of the same calculation at the same moment, then pause together to share results before the next step. This means their power draw rises and falls together. In extreme cases, aggregate power consumption within a single datacenter can oscillate by tens of megawatts as these phases alternate.⁴ Uptime Institute identifies repeated power fluctuation as a source of thermal stress beyond design limits on voltage regulators, solder joints, and capacitors, wear that is difficult to detect and often apparent only after a failure.⁵ Geometry compounds this problem. AI server boards carry unusually large packages, and for a given CTE mismatch the absolute difference in expansion scales with package dimension, concentrating strain at the outermost joints.

The same underlying concern shows up well beyond automotive, aerospace, and AI infrastructure. Consumer electronics, smartphones, tablets, and wearables, see frequent thermal cycling just from ordinary use.⁶ Additionally, medical devices, especially implantables and diagnostic equipment, combine compact form factor with long

service life and effectively zero tolerance for field failure. In every one of these cases, the underlying physics is the same: a board that expands unevenly puts strain exactly where components are least able to absorb it.

Solder joints are particularly vulnerable to differences in CTE. A component is rigidly attached to the board at both ends, so if the board expands more than the component (or expands differently in the thickness direction than the component expects), the solder joint absorbs the difference as mechanical strain. Repeat that thousands of times over the life of a product, through thermal cycling in the field or environments with wide temperature swings, and that strain accumulates as fatigue. Solder joint fatigue from thermal cycling is one of the most common failure mechanisms in electronics, and CTE mismatch between the board, the solder, and the component is what drives it. The damage usually starts in one specific place. Where the solder meets the copper pad, tin from the solder reacts with the copper and forms a thin layer of a different material called an intermetallic compound, only a few micrometers thick, at each end of the joint. That layer is brittle. The solder around it can deform slightly to absorb strain but the intermetallic cannot. The intermetallic also grows thicker throughout the lifetime of the joint.⁸ Once it is thick enough, cracks begin running through both the brittle layer and the solder, which is why the intermetallic is typically the first part of the joint to fail due to CTE mismatch.⁷ However, cracks can form in the laminate and solder ball as well, as is shown in the schematic and SEM image below.

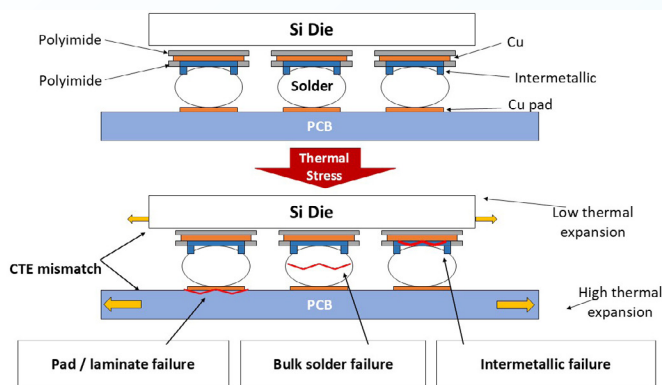


Figure 2: Schematic showing the shear stresses on the solder ball during thermal cycling with high CTE mismatches between layers.

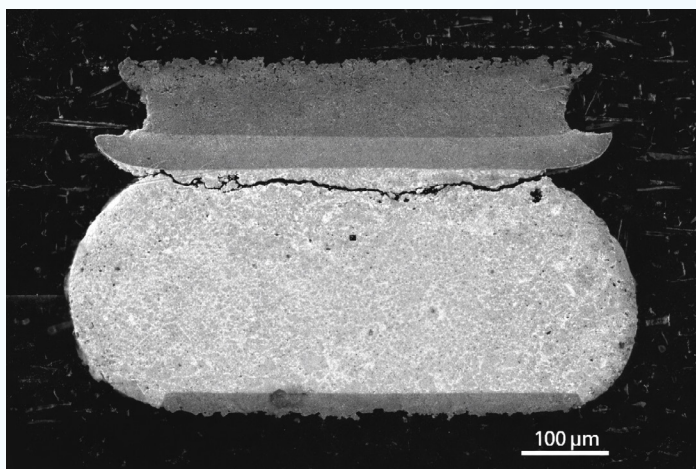


Figure 3: Scanning electron microscope image of a cracked solder joint.

Compounding the CTE mismatch further, a chip does not arrive as a bare piece of silicon. It comes as a package: a small assembly with the silicon inside and a body built from some combination of ceramic, glass-reinforced polymer, molding compound, and a metal lid or heat spreader. Every one of those materials has its own CTE, and they are not close to one another or to the board. Ceramics and the specialty alloys used for sealed packages expand far less than the laminate of the board. Metal lids and filled polymers expand faster,

matching or exceeding the board's in-plane rate. There is no single component CTE to design against, then. A ceramic package and a plastic one soldered to the same board present very different mismatches, so how much strain a joint absorbs per degree of temperature change depends on what the package is made of, not just on the board underneath it.

The board's thickness direction is where this risk concentrates. Plated through holes and vias run through the full thickness of the board, so as the board expands through its thickness, the copper plating inside those holes is stretched along with it. Copper and the board's laminate do not expand at the same rate through the board's thickness, so a board with high through-thickness expansion puts real strain on vias and can lead to via cracking or interconnect failure, particularly after repeated thermal cycles or extended time at elevated temperature.

This is why CTE is treated as a property to measure and control during board qualification, and why it's measured separately in-plane and through the thickness rather than as one number. The two directions behave differently because the reinforcing glass fibers in the laminate run in the plane of the board, constraining expansion in that direction, while nothing constrains expansion through the thickness. A board designer or process engineer qualifying a new laminate, evaluating a supplier, or investigating a field failure needs both numbers, and needs to know not just the average CTE but how it changes across the temperature range the board will actually see in the field.

What Is Thermomechanical Analysis (TMA)?

Thermomechanical Analysis measures how a material's physical dimensions change with temperature. A small probe rests in contact with the sample. As temperature is ramped (or held steady) in a controlled environment, any expansion, contraction, or softening in the material pushes the probe up or down, and that displacement is recorded continuously. The result is a direct, quantitative record of how a material's size changes as it heats or cools, not an inference from some other property, but a physical measurement of the dimension itself.

How It Works

The sample sits between a fixed stage and a probe under a small, controlled load. For this study, an expansion probe applied just 0.05 N of force, light enough to track dimensional change without deforming the sample. Temperature was ramped from -50°C to 100°C at 3°C per minute, adapted from ASTM E831, the standard method for TMA-based CTE measurement. Displacement versus temperature is recorded throughout the ramp, and the CTE is calculated from the slope of that curve at any given temperature. The temperature window was chosen to cover ordinary service and storage conditions for this board.

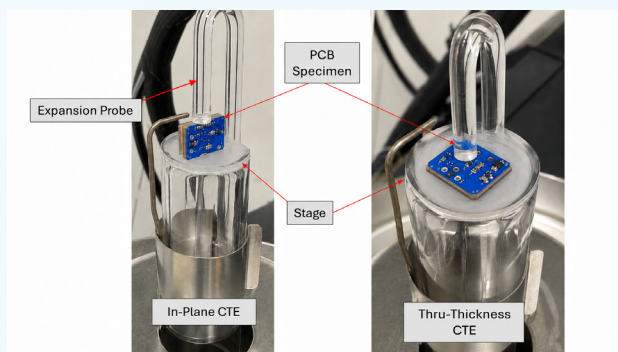


Figure 4: Images of experimental set up.

Instrument performance matters here too. The system used for this work, a TA Instruments Discovery TMA 450 EM, holds baseline drift under $1\text{ }\mu\text{m}$ across a -100°C to 500°C range and can apply loads as small as 0.001 N , precise enough to isolate genuine thermal expansion from measurement noise. Before running the PCB samples, the instrument was verified against a certified aluminum reference standard to confirm the measured CTE matched the known value.



Figure 5: At Covalent, we use a TA Instruments Discovery TMA 450 EM.

What TMA Tells You

A single TMA run can reveal several things about a material at once: its coefficient of thermal expansion, the temperatures at which it softens or transitions, and how dimensionally stable it stays under load across a temperature range. For materials that will experience real thermal cycling in the field, this is often the most direct way to answer the question, “how much will this actually move?”

What We Found

To see how a real board behaves, we cut test specimens from a printed circuit board using a diamond wire saw and ran Thermomechanical Analysis across a wide temperature range, -50°C to 100°C. Samples were tested in three directions: two in-plane orientations and one through the thickness of the board, so we could see whether the board behaved the same way in every direction or not.

In-plane, the answer was yes. Both orientations measured a CTE of about 17 to 18 $\mu\text{m}/\text{m}^\circ\text{C}$ consistently across the entire temperature range, with no meaningful difference between them. Rotate the sample 90 degrees within the plane of the board and the expansion behavior barely changes. That consistency comes from the glass fiber reinforcement woven into the laminate, which runs in the plane of the board and constrains expansion equally in both in-plane directions.

Through the thickness, the board behaved nothing like it did in-plane. CTE started around 42 $\mu\text{m}/\text{m}^\circ\text{C}$ near room temperature, already more than double the in-plane value, and climbed as temperature increased. By 90°C it reached 67.5 $\mu\text{m}/\text{m}^\circ\text{C}$, roughly four times the in-plane rate at that same temperature.

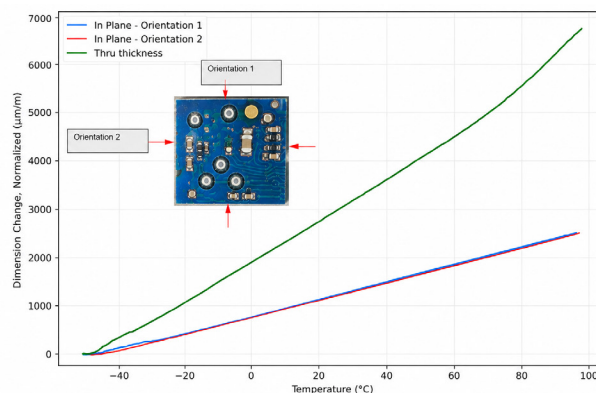


Figure 6: Graph of temperature vs dimensional change for all three measured orientations.

Two things stand out in that through-thickness result. First, the magnitude: even at the low end of the temperature range, the board expands more than twice as fast through its thickness as it does in-plane, confirming that a single CTE number can't describe this material. Second, and more important for anything that will see elevated temperature, the through-thickness expansion isn't linear. It accelerates as temperature climbs, with the rate of increase becoming noticeably steeper above roughly 60 to 70°C. A board designer using a single average CTE value for this material would underestimate how much it moves once temperatures climb into that upper range, exactly the range many boards see during elevated-temperature service.

Why This Specific Finding Matters

A multilayer PCB is anisotropic by construction, so substantially different in-plane and through-thickness CTE values are not unexpected. The mechanism behind the difference is worth stating explicitly. The glass fibers are woven into a flat cloth that lies in the plane of the board: there is glass running east–west and north–south, and no glass running up. In the plane of the board, those fibers are continuous and bonded to the resin, so the two are forced to stretch by the same amount. In other words, they are mechanically in parallel with the much stiffer glass governing the result. Out of the plane of the board there is no fiber reinforcement at all. The layers act in series, the epoxy expands essentially unrestrained, and the in-plane expansion the glass suppresses is redirected into the z direction.

What matters for reliability is accurately characterizing that directional and temperature-dependent behavior so it can be considered alongside the CTE of other materials in the package, such as solder joints, components, underfills, and encapsulants. Differences in thermal expansion between these materials can generate warpage, interfacial stresses, and strain in solder joints and vias during temperature changes and repeated thermal cycling. Measuring CTE as a function of both direction and temperature therefore provides more representative material inputs for thermomechanical models than relying on a single average CTE value.

How We Can Help

TMA lets you measure exactly this kind of behavior directly, in whatever orientation and temperature range your material will actually see. Covalent runs CTE and thermal transition characterization across materials and orientations, whether you're qualifying a new PCB laminate or any material where thermal expansion is part of the design margin.

Citations

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