

The background of the slide features a grid of blue squares. The top-left square is a solid medium blue. The other squares contain various abstract patterns of overlapping lighter and darker blue shapes, creating a modern, geometric aesthetic.

What Really Failed?

Understanding Failure in
Materials, Components,
and Assemblies

COVALENT
Material Insights



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Introduction: Failure Rarely Starts Where You First Notice It

When a product fails, the visible problem is rarely the whole story.

A cracked weld, an intermittent electrical connection, a delaminated capacitor termination, a solder joint anomaly, or a fractured casting may look like isolated defects at first glance, but in practice, those symptoms are usually just the final expression of a deeper problem rooted in materials, process conditions, design, contamination, geometry, or service stress. Failure analysis is the discipline of uncovering that deeper story. It is how engineers move beyond asking what broke to asking the more important question: why did it break, and what should be done next?

At Covalent, we handle many types of failure analysis including polymer, ceramics, glass and more. This eBook will place a special focus on failure analysis which often falls into two closely related worlds. One is metallurgical failure analysis, where the focus may be a weld, a fracture surface, a heat-affected zone, a casting defect, or the microstructure of a metal component. Another is electronics and PCB failure analysis, where the focus may be solder joints, plated-through-holes, wire bonds, component terminations, delamination, contamination, or internal defects hidden inside an assembly. These may sound like separate problems, but they are connected by the same goal: determine the true mechanism of failure and provide data that helps the client make a better decision.

That is important because failure rarely begins at the moment when a part stops working. A weld may have looked acceptable from the outside while containing craters, porosity, incomplete

penetration, or cracking that reduced its structural integrity from the beginning. A solder joint may have passed a cursory inspection while still suffering from non-wetting, interfacial separation, voiding, or contamination that later led to electrical instability or early-life failure. A cast metal component may fracture in service, but the real origin may trace back to a shrinkage void near a high-stress feature that quietly weakened the part long before it broke. In each case, visible failure is only the end of a chain of events.

That is why good failure analysis is never just about taking a picture. It is a structured investigation. It may begin with electrical testing, visual inspection, optical microscopy, and X-ray imaging. From there, the path may move into cross-sectioning, parallel lapping, dye-and-pry, SEM/EDS, fractography, metallography, or other targeted methods depending on the question being asked. In electronics work, one technique may reveal that a plated-through-hole has pull-away, PCB cracking, and solder/pin separation, while another shows that a connector pin still carries intact gold plating in a region where solder never properly wetted. In metallurgical work, cross-sections can reveal whether a weld truly penetrated the joint, whether porosity clustered near a crater, or whether a crack initiated at a stress concentrator such as a root defect, toe defect, or casting void.

This eBook is about that process of getting to the root cause.

It is designed to help readers understand how PCB failure analysis and metallurgical failure analysis work, what kinds of defects commonly appear, and why those defects matter in the real world. Along the way, we will look at recurring problems such as weld porosity,

cratering, incomplete penetration, and cracking; solder non-wetting, voiding, delamination, and interfacial separation; plated through hole defects; capacitor termination failures; connector pin contamination; and fracture features that reveal where a crack started and how it propagated. We will also show why no single method tells the whole story. The most useful answers come from combining techniques and interpreting them in context.

Just as importantly, this is not only a book about defects. It is a book about decision-making. Clients come to failure analysis labs because they need more than images. They need to know whether a process should be changed, whether a supplier issue may be involved, whether a design feature is creating stress concentration, whether a reliability risk is isolated or systemic, and what next step will most efficiently reduce uncertainty. A useful investigation turns physical evidence into practical direction.

In the chapters that follow, we will walk through the failure analysis approach that has been developed and refined by experts over decades and is continually adapted by Covalent for new products and their corresponding failure modes.

The Covalent Workflow: From Symptom to Root Cause

Covalent adheres to this overall problem-solving process:

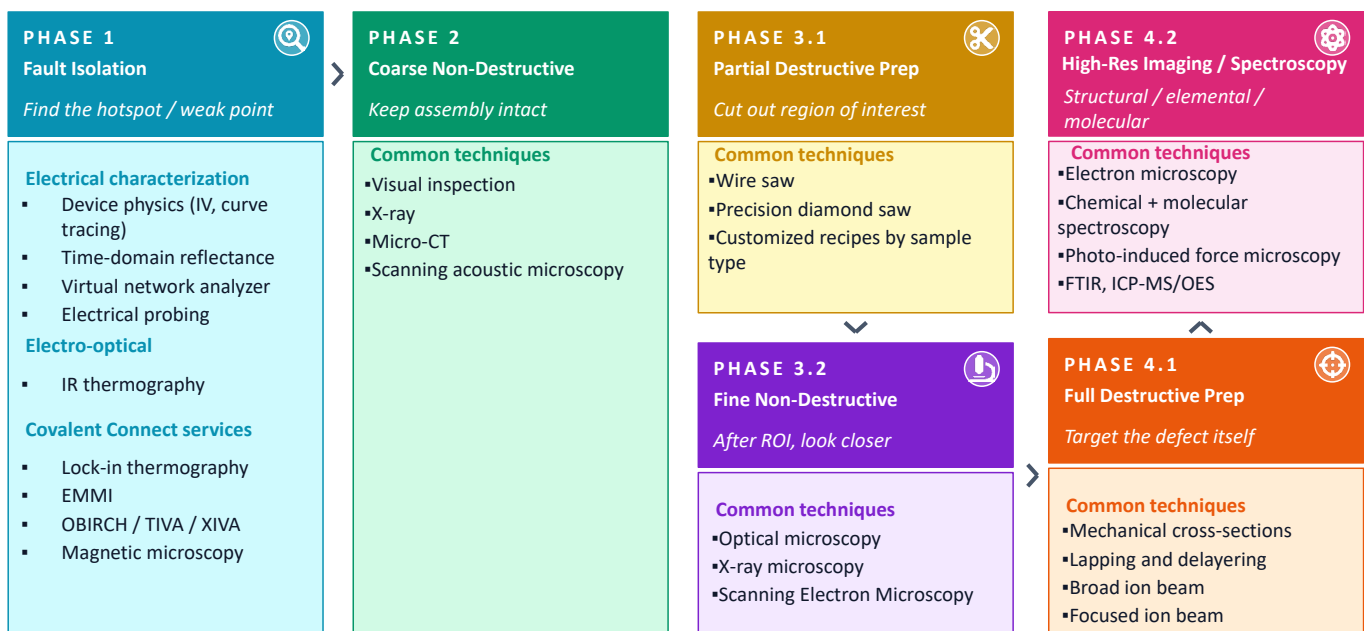
Define the problem.

1. Gather background and service history.
2. Examine non-destructively.
3. Examine destructively.
4. Analyze chemistry and microstructure.
5. Synthesize root cause and corrective action.

Figure 1: Failure analysis workflow. Covalent can accommodate pieces of this workflow or customized to the needs of the client.

Failure Analysis Workflow

Progressive technique escalation — non-destructive → destructive



Start Non-Destructively

At Covalent, failure analysis usually begins with the least invasive methods possible. The first step is careful visual inspection and photo documentation, which helps establish the as-received condition and often reveals important surface clues before any material is cut, polished, or otherwise altered. For welds, different lighting strategies can make a major difference. Oblique (dark field) lighting, for example, is especially useful for bringing out subtle surface topography, crack paths, chevron patterns, crater features, and other signs that may point toward where a failure started and how it progressed. This kind of front-end documentation is a core part of the workflow for both metallurgical and electronics investigations.

In the example below, a client sent a camera device and reported intermittent signal loss on a high-speed PCB.



Figure 2: Sample as-received, front.



Figure 3: Sample as-received, back



Figure 4: Optical image of PCB with suspect regions indicated for electrical testing.

After performing electrical testing at suspect locations, we developed a working hypothesis of possible discontinuity in a solder ball, trace, or microvia.

When the failure mechanism may be hidden below the surface, Covalent moves to non-destructive imaging. Standard 2D X-ray is often the first choice for evaluating internal features in assemblies because it is fast and effective for locating hidden internal anomalies such as voids, bond issues, and solder-related defects. This method captures variations in X-ray absorption based on the material density and thickness, allowing visualization of features such as voids, cracks, misalignments, or other defects.

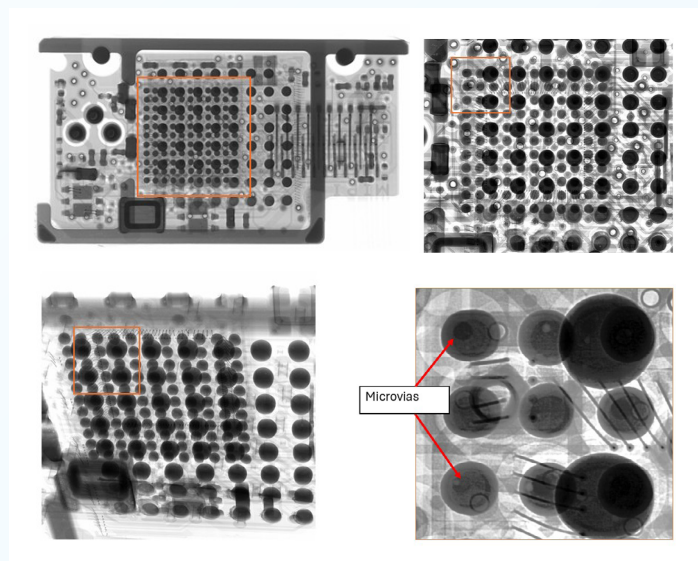


Figure 5: X-ray images of PCB.

In this example, the X-ray images revealed no misalignment, voids, cracks, clear opens, incomplete vias or foreign particles/defects.

If the internal structure needs to be resolved non-destructively in three dimensions, micro-CT becomes the next step. Micro-CT is a non-destructive X-ray imaging technique that reconstructs the internal structure of a sample in three dimensions with micrometer-scale resolution. These methods are especially valuable when the analyst needs to localize an internal defect before deciding where to section, or when the customer wants to preserve the sample as much as possible.

In PCB work, scanning acoustic microscopy, or SAM, is another important non-destructive tool because it excels at detecting delamination and larger crack-like separations within layered structures. SAM is a non-destructive imaging technique that uses focused ultrasound to inspect internal features and interfaces inside a part. Rather than relying on visible light, it sends an acoustic pulse into the sample and measures the reflected signal as that pulse encounters changes in material. Every interface reflects sound differently depending on the acoustic impedance of the materials involved. In practical failure analysis, that matters because a well-bonded interface behaves very differently from an interface that contains an air gap, crack, or separation.

The reason SAM is so powerful for PCB and electronic-package analysis is simple: air gaps reflect ultrasound extremely strongly. Even very thin separations can create a large acoustic response. That makes SAM exceptionally sensitive to defects such as delamination, cracking, voiding, adhesion loss, and interfacial separation. In layered electronic assemblies, those are often the very defects that drive intermittent behavior, loss of reliability, or complete field failure.

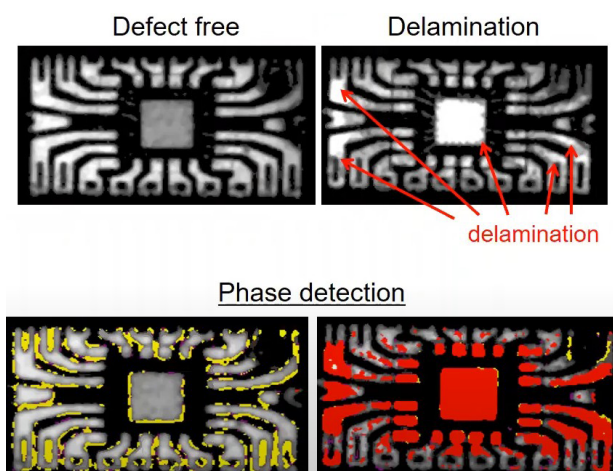


Figure 6: SAM with phase detection. Delaminated regions appear as bright areas (upper image) or marked as red using our SAM's built in phase detection tool. Image courtesy of PVA Tepla.

Each non-destructive technique has its own advantages. SAM is best for larger delaminations/separations (greater than 5µm), especially in layered electronic structures. Micro-CT is better for internal features that need three-dimensional localization. SEM comes later, when the investigation requires the finest level of detail at or near the surface of a prepared section. In practical terms, Covalent often follows a usable progression: SAM for larger delaminations, micro-CT for smaller hidden internal features, and SEM for the features below that size range where high-magnification imaging is needed to understand the defect.

This staged approach matters because it helps preserve evidence while making the destructive steps more targeted and more informative. Instead of cutting blindly, Covalent uses the early non-destructive work to narrow the search, choose the right cross-section plane, and increase the odds of capturing the actual

defect mechanism. That is how the workflow moves from a vague symptom—an intermittent board, a suspicious weld, a cracked hub, a failed connector—to a defensible root-cause story built from the right technique at the right scale.

Turn to Destructive Analysis When Needed

Non-destructive tools are the right place to start, but they do not always tell the full story. Optical imaging, X-ray, and SAM can point to a suspect region, yet many failure mechanisms only become obvious once the part is physically opened, sectioned, or stripped down. Destructive methods are often what turns a vague symptom into a defensible root-cause conclusion. Covalent's workflow uses these methods strategically: once the likely failure region is identified, the goal is to expose the true interface, fracture surface, or internal structure with as little ambiguity as possible.

A mechanical cross-section is one of the most important destructive tools in failure analysis. The sample is cut, mounted, polished, and then examined optically or in the SEM to reveal internal interfaces and buried defects. In the case of electronic assemblies, Cross-sections can expose solder fill, plated through hole integrity, pad lift, cracking, separation, delamination, voids and non-wetting that may only be hinted at in X-ray images.

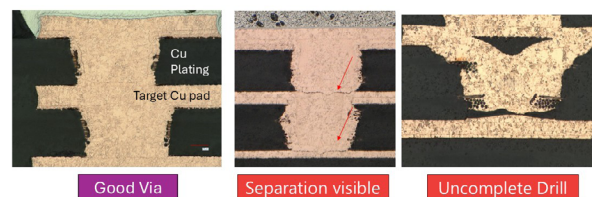


Figure 7: Optical microscopy of mechanical cross-sections used to inspect microvias.

Parallel lapping is a destructive preparation method in which material is removed in controlled increments, so analysts can inspect a part at multiple depths. It is especially useful when a single cross-section might miss the true defect location, such as in solder joints, plated through holes, connectors, and multilayer PCB structures. This method is also commonly used to expose defects in integrated circuits.

Parallel lapping is especially powerful when the defect may be hiding in only one small plane or when the analyst needs to inspect many similar structures across depth. Instead of taking one cut and hoping it lands in the right place, the sample is progressively lapped through multiple planes. This is extremely useful for dense PCB connectors, plated structures, and multilayer assemblies where one isolated section may miss the problem entirely. Covalent uses lapping to follow different trace paths and inspect connector and solder behavior through the board thickness.

Dye and pry analysis is a targeted destructive method used mainly for solder-joint reliability problems, particularly with area-array packages where cracks can hide beneath the component. In this procedure, dye is allowed to wick into pre-existing cracks or separations, and then the component is mechanically removed. The fracture surfaces are examined for where the dye penetrated, which helps show whether a crack already existed before the part was pried off. Dye and pry can be especially powerful as part of Covalent's PCB workflow for solder-joint analysis because it provides exactly the kind of insight that matters when a customer is trying to determine whether a field failure came from assembly, fatigue, or some later handling event.



Figure 8: Solder joints on the board (left) and component (right) sides of the PCB, are marked by red dye, indicating head-in-pillow defects.

Decapsulation becomes necessary when the suspected failure is inside a packaged electronic component rather than in the solder joint or board itself. If X-ray or CT cannot resolve the defect clearly enough, the package material can be chemically or mechanically removed to expose the die, wire bonds, and internal interconnects. This is often the next step for wire-bond failures when non-destructive imaging is not enough, with the goal of reaching the bond without destroying the feature of interest.

This matters because wire-bond and internal package failures are often too small, too buried, or too geometrically complex to diagnose with external inspection alone. Once opened, the analyst can directly inspect bond lift, misalignment, contamination, cracking, evidence of electrical overstress or electrostatic discharge.

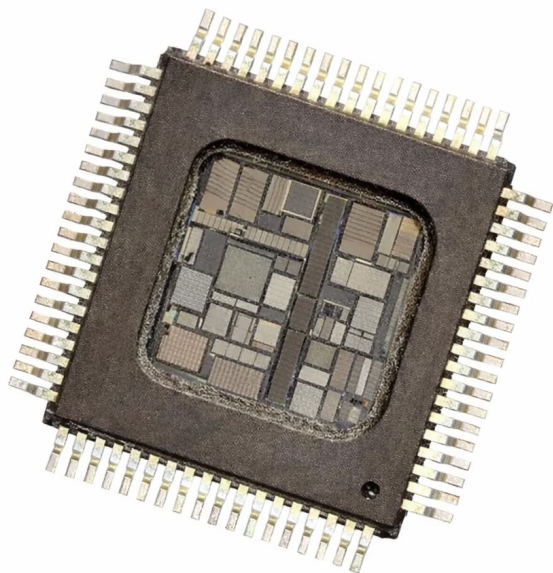


Figure 9: A chip after chemical and mechanical decapsulation.

A related step is delayering, where material is removed layer by layer so that the analyst can reach the active structures on the die. This is crucial when the failure may involve internal metallization, localized damage, or a feature deep inside the device stack. Die failures may require decapsulation first and then etching or further electronic microscopy, depending on where the suspected failure lies.

This is why destructive failure analysis is often the only way to see the truth. Many important defects are not just hidden—they are ambiguous until the true interface is exposed. A void on X-ray may or may not matter. A suspicious acoustic signal may or may not correspond to a real separation. A surface crack may be the main failure mechanism or merely collateral damage. Destructive methods remove that uncertainty by opening the structure, revealing the actual geometry,

and letting the analyst inspect the real failure plane. Failure analysis at Covalent repeatedly shows this pattern: cross-sectioning confirms whether a solder joint is truly non-wetted, whether a weld actually penetrated the joint, whether contamination remains on a pin surface, whether a capacitor termination is delaminated, or whether a fracture initiated from a casting defect rather than from bulk microstructure differences.

In practice, the best analysts do not treat destructive work as a last resort born of impatience. They treat it as the moment when the investigation becomes decisive. Once you have narrowed the search with the right non-destructive tools, destructive FA is often what transforms suspicion into evidence and evidence into root cause. That is where failure analysis stops searching broadly and starts isolating the needle in the haystack—pinpointing the exact mechanism responsible for failure.

Use Chemistry and Microstructure to Finish the Story

By the time a failure analyst reaches this stage, obvious physical evidence has usually already been found. The crack has been located, the suspect solder joint has been exposed, or the fracture surface has pointed toward a likely origin. But seeing a defect is not always enough. The final step is often to understand what the material was, how it was built, how it changed, and why it failed in that specific way. That is where chemistry and microstructure come in. These tools do not replace good visual inspection or fracture analysis. They sharpen it. They help confirm whether a dark feature is contamination or just contrast, whether a brittle crack followed grain boundaries, whether a weld was improperly processed, whether a polymer

became thermally degraded, or whether local mechanical properties drifted out of spec.

One of the most important tools here is SEM/EDS. Scanning electron microscopy gives much higher-resolution views of fracture surfaces, interfaces, pores, inclusions, coatings, and crack morphology than optical microscopy alone. Energy-dispersive X-ray spectroscopy then adds chemistry, allowing the analyst to ask what elements are present in a suspicious region. In practical failure analysis, this can mean showing oxides on a crack surface, spotting contamination on a pin or solder interface, checking whether a weld inclusion is compositionally unusual, or confirming whether corrosion products are present at the site of failure. This is often the point where a defect stops being merely visible and starts being interpretable. Without chemical analysis, a crack reveals only its morphology. A crack lined with oxygen, sulfur, or unexpected residues reveals the degradation mechanism and environmental exposure history.

In solder and PCB work, SEM/EDS is especially valuable because many failures involve tiny interfaces where morphology and chemistry both matter. A joint may look separated in cross-section, but SEM can reveal whether the surfaces actually wetted and fused, whether an intermetallic layer formed properly, or whether the interface has oxidation or contamination. The same is true for plated-through-holes, microvias, and connector pins. Sometimes the key question is not just whether a separation exists, but whether it formed because of poor plating, contamination, incomplete metallurgical bonding, or some later use-driven degradation. SEM/EDS is often the technique that answers that question.

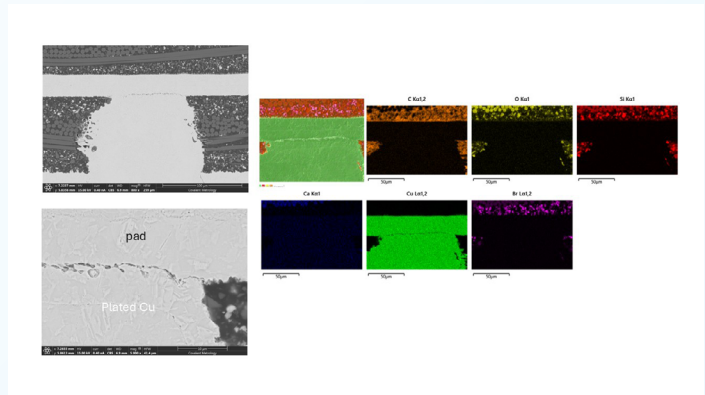


Figure 10: SEM images revealing a crack between the pad and the plated copper. No oxidation or contamination defects were detected with SEM/EDS.

When grain structure matters, EBSD can take the analysis further. Electron backscatter diffraction is not always necessary, and in many routine solder or PCB cases it may be more information than the customer needs. But in metallurgical failure analysis, especially for welds and fracture cases, grain orientation, grain boundary character, and local crystallographic texture can matter a great deal. EBSD helps reveal whether a crack is following grain structures, whether the weld zone differs substantially from the surrounding base metal, and whether the local microstructure points toward an unfavorable thermal history or process condition. In other words, if standard imaging shows that a crack followed the microstructure, EBSD helps explain which microstructure and why that matters.

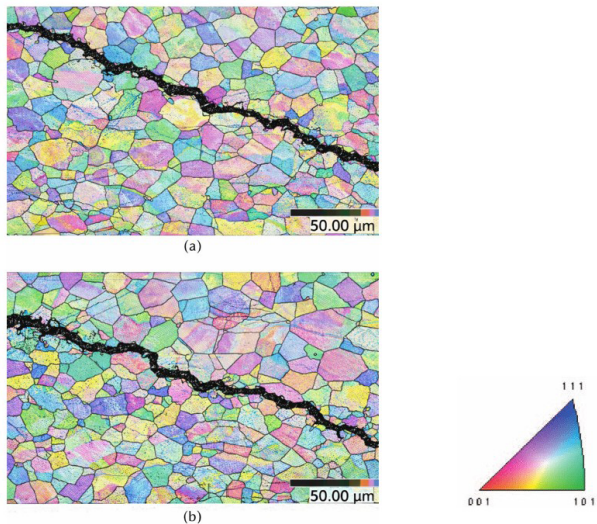


Figure 11: EBSD map showing a crack propagating along a grain boundary.

Sometimes, grains and cracks are large enough that EBSD is not required. Instead, chemical etching can be used to reveal grain boundaries which are then imaged optically. A polished cross-section by itself can reveal voids, cracks, lack of fusion, and gross geometry. But once the surface is properly etched with chemicals, the microstructure comes alive. Grain boundaries become visible. Heat-affected zones appear. Weld penetration, fusion profiles, segregation patterns, and microstructural transitions become much easier to interpret. Different materials require different etchants, and that matters because the purpose is not to attack the sample randomly. The goal is to reveal the structure that caused the failure.

In the example shown below, a customer came to us with a magnet failure in a DC generator. Etching on the cross section revealed the microstructure and intergranular cracking was observed throughout the magnet along the grain boundaries.

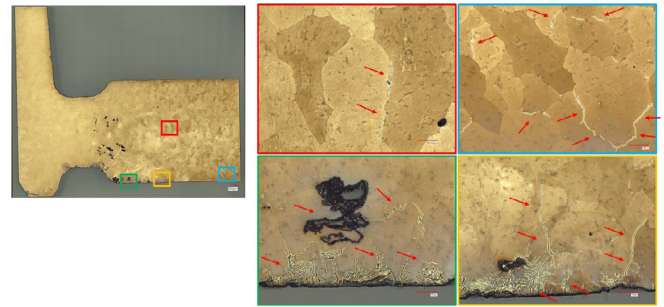


Figure 12: Optical images of the post-etched magnet with close-ups of the indicated regions. The images reveal cracks propagating along grain boundaries.

SEM and EDS examination on this part showed a concentration of sulfur at the crack boundary, which is indicative of corrosion cracking.

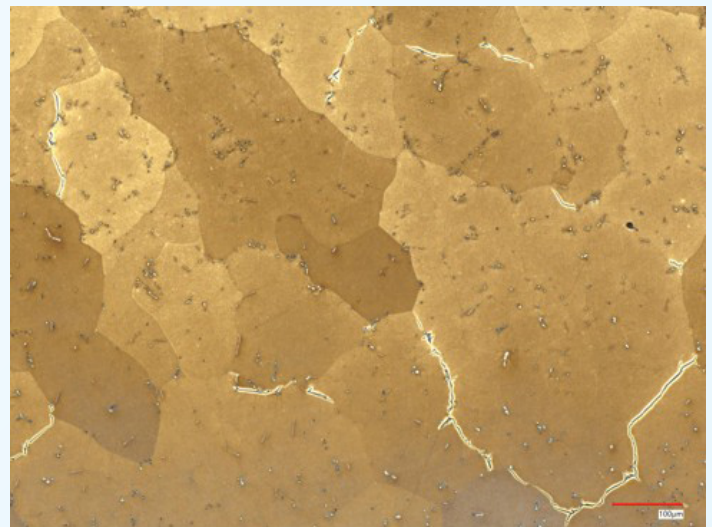


Figure 13: Hidden cracks in the magnet grew silently causing debris to build up in the housing that eventually brought the generator down — our analysis revealed the true failure path.

Hardness testing adds another layer of insight by turning a visual suspicion into a measurable mechanical property. If a region looks embrittled, over-hardened, under-processed, or softened by heat, hardness data can help confirm that

impression. This is useful in welds, heat-treated metals, coatings, and certain fracture cases where the analyst needs to know whether the failed region had the expected resistance to deformation. Hardness alone is rarely the whole answer, but it can be a strong supporting clue. A weld that looks unusual and also shows an abnormal hardness gradient tells a much stronger story than appearance alone. The same goes for a component that appears properly joined but has local mechanical properties inconsistent with the intended design or process.

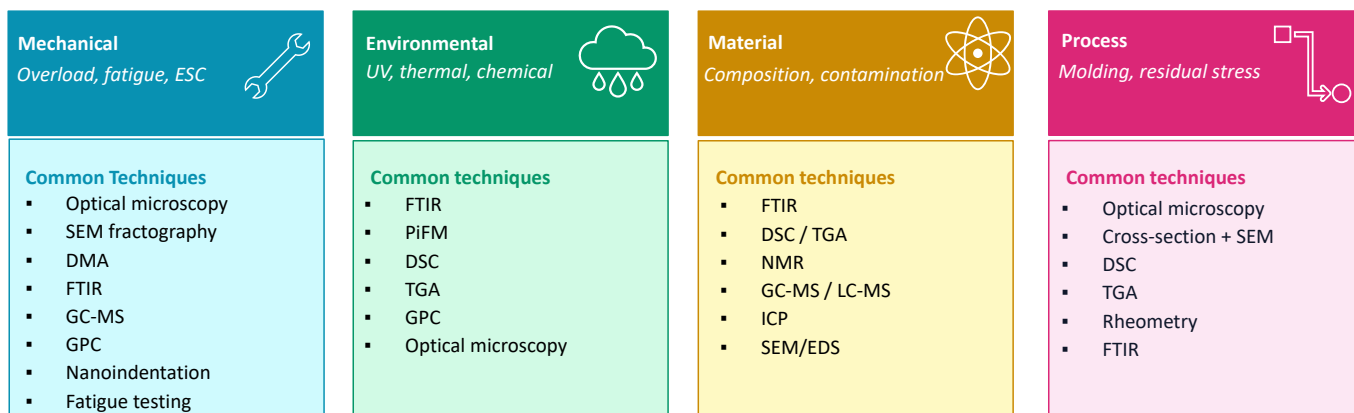
For polymer fracture cases, the toolkit expands beyond imaging into thermal and chemical analysis. DSC, TGA, and FTIR are particularly useful here because polymer failures are often driven by chemistry that cannot be

seen directly in a cross-section. Differential scanning calorimetry (DSC) can reveal changes in glass transition temperature (T_g), crystallinity, degree of cure, or thermal history. Thermogravimetric analysis (TGA) can help identify thermal degradation, decomposition, or unusual mass-loss behavior. Fourier transform infrared spectroscopy (FTIR) can detect organic contamination, compositional shifts, oxidation-related changes, or evidence that the material is not what it was supposed to be. This matters because polymer parts often fracture for reasons that look mechanical on the surface but are rooted in chemistry: aging, overheating, environmental exposure, plasticizer loss, contamination, or incorrect formulation. When a plastic or adhesive fails, microscopy may show where it broke, but thermal and spectroscopic tools often explain why the material became vulnerable in the first place.

Figure 14: A decision tree for choosing the right technique when faced with different polymer failure modes.

Polymer Failure Analysis Decision Tree

Failure Types



In some cases, XRD for residual stress is the missing piece. Not every failure requires this level of analysis, but when geometry, processing, or service conditions suggest that locked-in stress may have contributed, residual stress measurements can be extremely informative. Sharp corners, aggressive machining, forming, welding, and thermal gradients can all leave a part carrying stress before it ever gets used. If a crack initiates in a region with no obvious inclusion, no major microstructural defect, and no chemistry anomaly, residual stress can become a very plausible contributor. This is particularly relevant when the failure occurs near a geometric transition or in an area where deformation and constraint would be expected to concentrate stress.

The bigger point is that failure analysis is not one technique. It is a decision tree. Good analysts do not throw every tool at every part. They start with the most direct evidence: fracture surfaces, visible damage, cross-sections, and obvious structural defects. Then they ask what is still unknown. Is the problem contamination? Is the alloy correct? Did the microstructure become embrittled? Are the local mechanical properties wrong? Could residual stress or thermal degradation be part of the story? Each answer determines the next step. That is how failure analysis moves from symptom to root cause.

Covalent is proud to own a full suite of advanced instrumentation. However, the real value in our FA workflow is not using all the tools available to us. The value is in knowing when to use each technique. When features are small enough to require SEM, when grain structure matters enough for EBSD, when etching will reveal more than polishing alone, when hardness data will strengthen the case, and when polymer chemistry or residual stress needs to be brought

into the investigation. Real failure analysis is not a single test. It is a disciplined progression from visible evidence to material behavior, from structure to chemistry, and from observation to explanation.

Failure Analysis Is Not Just Defect Hunting

One of the biggest mistakes in failure analysis is assuming that the first visible flaw must be the root cause. Failures are rarely that simple. A crack, void, inclusion, or contamination site may be important, but the real question is always deeper: did that feature actually cause the failure, or is it just along for the ride?

Sometimes the material is perfectly acceptable, but the design creates a bad load path. A sharp corner, thin section, abrupt geometry change, or poorly supported joint can concentrate stress in a way that makes failure almost inevitable, even when the material itself meets expectations. In those cases, the analyst may find a crack, but the crack is only the final symptom of a design-level problem.

Sometimes the opposite is true. The design may be sound, but the process introduces weakness. A weld may have insufficient penetration. A solder joint may have non-wetting or separation. A plated through hole may not have formed a reliable metallurgical connection. In those cases, the geometry is not the villain. The process is.

And sometimes the situation is more subtle still. A visible defect may exist, but it may not be the real cause of failure. A dramatic-looking void may not be in a critical location. A surface blemish may be harmless. A crack may have formed late, after the true damage had already occurred somewhere else. Meanwhile, a much smaller and less obvious interface issue—a thin contamination layer, a weak bond, a poorly

formed intermetallic, a local microstructural mismatch—may be the feature that actually mattered. Good failure analysis separates interesting defects from causal defects.

This is where interpretation becomes more valuable than raw imaging. A good lab does not just generate pictures, spectra, and hardness numbers. It explains what those findings mean in the context of mechanism. Is this overload or fatigue? Is this non-wetting or post-failure pull-away? Is this contamination actually harmful, or merely present? Is the joint weak because of chemistry, microstructure, geometry, or service stress? That interpretive layer is what turns lab work into engineering guidance.

This is also where Covalent's approach stands out. The goal is not simply to document what a part looks like after it breaks. The goal is to determine why it broke in the first place, whether the controlling issue lives in the material, the manufacturing process, the assembly, the geometry, or the way the part was used. That means combining imaging with measurements, and measurements with judgment. It means moving beyond defect detection toward mechanism-based conclusions and practical next-step recommendations. It also means working closely with our clients as partners in the failure analysis process to ensure we are delivering the most actionable results.

In other words, failure analysis is not just about finding something wrong. It is about finding out what mattered. The best failure analysis does more than document damage. It gives customers a path forward. It helps them identify the real mechanism behind the failure, reduce repeat problems, improve reliability, and make smarter engineering decisions with confidence.

Welds and Solders: Built for Different Jobs, Fail in Different Ways

At Covalent, we spend a significant amount of time analyzing two types of systems: welded structures and PCB assemblies. While these may seem unrelated, both ultimately come down to one thing—joints. And not all joints fail for the same reasons, because not all joints are trying to do the same job.

At a glance, both welds and solders may appear to be simple connections between two materials. But in practice, they belong to two vastly different worlds. A weld is usually expected to provide structural integrity. A solder joint is usually expected to provide electrical continuity, often while also tolerating thermal cycling, vibration, and mechanical strain. That difference in purpose changes everything about how the joint is made, how it fails, and how it should be analyzed.

Welds: Built for Structure, Strength, and Load

A weld is typically used when two parts must act as one continuous structure. In that setting, the joint is expected to carry load, resist fracture, and survive real-world service conditions. At Covalent, this kind of work often involves metals such as titanium, stainless steel, aluminum, and carbon steel, across applications ranging from biomedical devices to automotive hardware and industrial components. Because the weld is structural, the key question is not simply whether the joint exists, but whether it was formed correctly enough to deliver the strength and integrity the design requires.

In weld failure analysis, we look for several common defect types that can weaken a joint or create sites where cracking begins.

- **Craters are depressions** that form at the end of a weld bead when the weld pool solidifies with insufficient fill at the termination point. While a crater is not always considered a defect by itself, it often leads to cracking because the molten metal shrinks and solidifies unevenly.
- **Overlap, sometimes called cold lap,** occurs when excess weld metal rolls onto the base material without properly fusing, leaving a sharp notch that can concentrate stress.
- **Undercut** is a groove worn into the base metal at the edge of the weld, usually caused by welding conditions that remove too much material and leave behind a thinner, weaker section.
- **Porosity**, including subsurface pores and surface-breaking pinholes, refers to gas-filled cavities trapped in the weld as it solidifies; these voids can act as starting points for cracks.
- **Incomplete penetration** happens when the weld does not fully fuse through the joint thickness, leaving an unfused region and often a sharp discontinuity at the weld root that acts as a stress riser.

In each case, the concern is not just appearance. These features can create weak spots, reduce the effective load-bearing cross-section, and increase the chance of crack initiation and growth. In a good weld, the joined area should act like a strong, continuous section of material. But if there are voids, cracks, pores, or unfused regions, part of that area is missing or not really bonded. So even if the weld looks full size from the outside, the amount of metal that can truly resist force is smaller.

When investigating welds, Covalent will often look at three common locations where cracks can start or grow:

- **The weld root** is the deepest inside part of the joint, where a lack of full penetration can leave a sharp notch.
- **The weld toe** is the edge where the weld bead meets the surface of the base metal, which is another common place for stress to concentrate.
- **The fusion face** is the area along the side of the weld where the melted weld is supposed to bond fully to the surrounding metal.

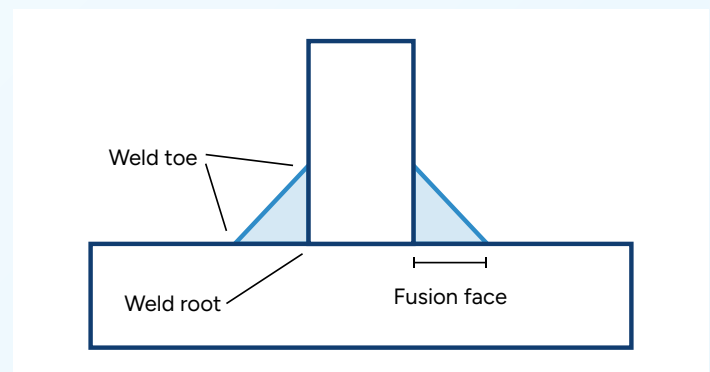


Figure 15: The anatomy of a weld.

In one investigation on an aluminum frame from a heavy equipment manufacturer, our FA engineers started their work with a visual inspection, noting features like pores, weld craters and undercuts which can create weak points where cracks begin and grow.

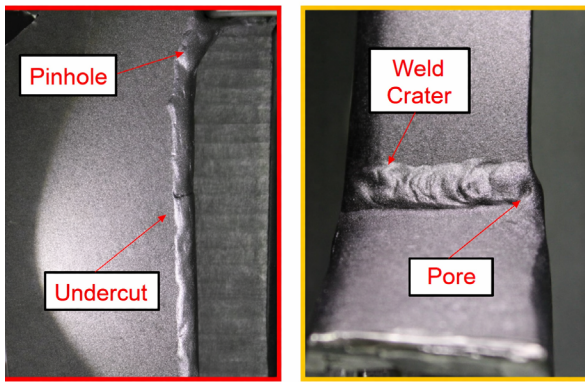


Figure 16: Close-up photo documentation of a corner joint weld where undercut and pinhole porosity were observed. An additional weld joint on the side walls exhibits weld cratering and porosity on the weld face.

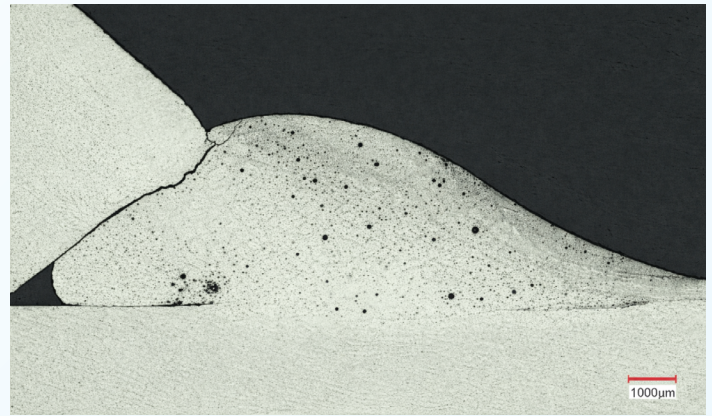


Figure 18: Several types of cracking were observed at the root, toes, and fusion faces of the weld. The weld exhibits small pores throughout. Additionally, the weld did not fully penetrate the intended joint.

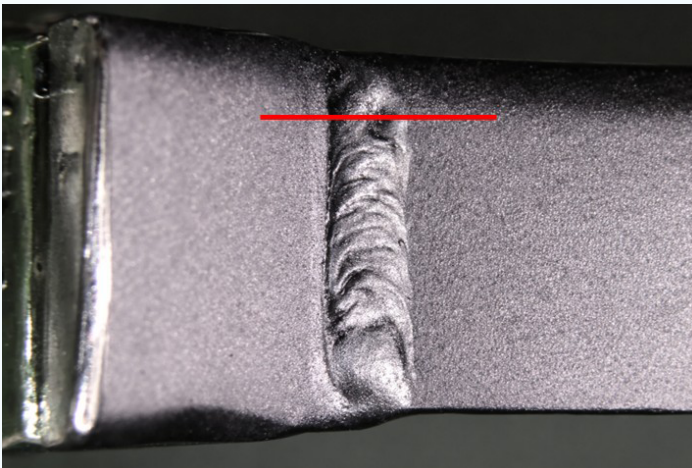


Figure 17: Optical image indicating where the cross-section will be cut.

Metallurgical failure analysis often starts by asking a structural question: Did this joint truly become one sound piece of metal, or did hidden defects undermine it from the start? The answer usually comes from visual inspection, optical microscopy, cross-sectioning, and, when needed, SEM/EDS or more advanced materials characterization. Weld analysis is often very geometry- and process-driven. The analyst wants to know what the weld bead looks like, how deeply the weld penetrated, whether the microstructure is appropriate, whether there are inclusions or contamination. Whether the observed defects can be tied back to welding conditions such as heat input, travel speed, surface condition, or joint preparation must also be understood.

Solder Joints: Built for Electrical Interconnection, Reliability, and Interfaces

Solder joints live in a different universe. Their primary role is usually not to hold up a heavy load, but to create a reliable electrical connection between component, pad, pin, or plated-through-hole. They are formed at lower temperatures than welds, often through

surface-mount technology (SMT) reflow processes in printed circuit board assembly, and they fail by a different set of mechanisms. In simple terms, welds are about strong structural connections while solder joints are mainly electrical. But in both cases, the joint must still form properly—because whether it is carrying force or carrying current, a weak connection can still be a failure if the joint cannot do the job it was built to do.

In PCB and electronics work, the recurring questions are often about wetting, coalescence, separation, delamination, voiding, cracking, bridging, missing solder, or defects in the board and component interfaces themselves. In PCB failure analysis, the problem is often not limited to the solder alone. A plated-through-hole can exhibit barrel cracking or copper discontinuity. A board can exhibit delamination. Components can separate internally. A hidden wire bond can fail at the die attachment point. In other words, electronics failure analysis is often really analysis of a whole interconnect system, not just a deposit of solder. We'll take a close look at those other failure modes in later chapters of this eBook. For now, let's narrow in on solder-related failures.

A solder joint may appear present and still be weak, poorly adhered, or electrically unreliable.

Common solder problems include:

- **Cracks:** fractures that form within the solder itself or at the interface between the solder and the pad, pin, or component termination. They can start small and grow under thermal cycling, vibration, or mechanical loading, eventually causing intermittent or complete electrical failure.

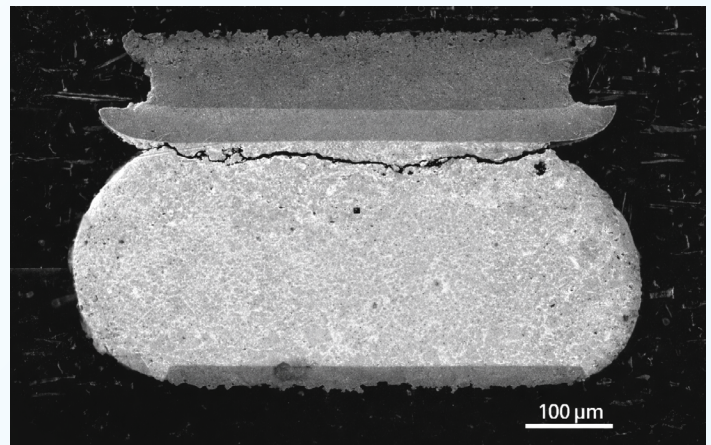


Figure 19: SEM image of solder ball cross-section showing a large crack.

- **Delamination:** separation between adjacent layers within a laminated structure, such as between prepreg plies, copper foil and dielectric, or within a component termination stack-up. In PCB work, this often refers to separation within the laminated board structure or within a component termination. Delamination usually indicates a loss of adhesion and can be caused by heat, mechanical stress, poor processing, or material incompatibility.

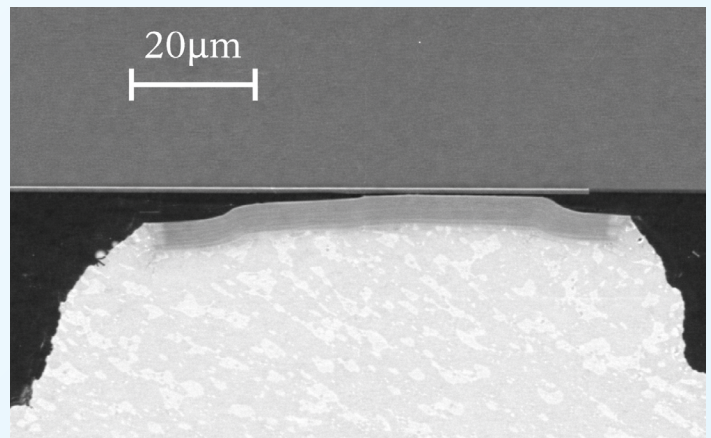


Figure 20: SEM image of solder ball showing delamination.

- **Head-in-pillow defects:** when the solder on the component side and the solder on the pad side melt but do not fully merge into one continuous joint. In this case, the solder does not fully coalesce, leaving a top rounded solder mass and a bottom rounded solder mass instead of one unified connection. It is typically caused by component or board warpage during reflow, making it a serious assembly defect because the joint may look acceptable from the outside while being electrically unreliable.

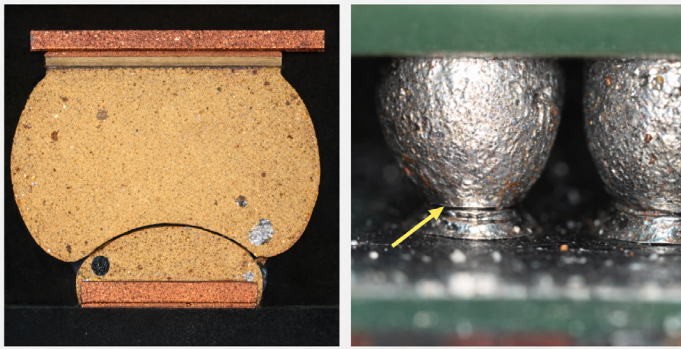


Figure 21: Optical images of solder ball showing head-in-pillow defect.

- **Solder bridging:** solder unintentionally connects two adjacent solder points that should remain electrically isolated. In other words, excess solder forms a bridge between neighboring leads, pads, or pins, creating an electrical short.

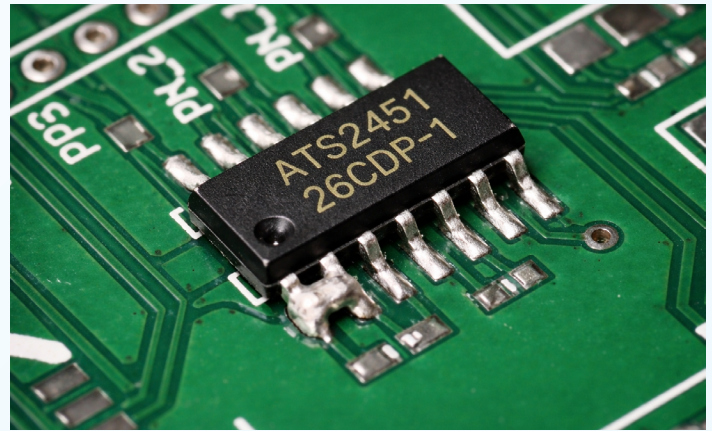


Figure 22: An integrated circuit with solder bridging.

- **Open solder:** the intended solder connection is missing or incomplete enough that no functional electrical path is formed. To put it simply: sometimes the solder is just missing. In the real world, this can show up as a completely absent joint or as such poor wetting/coalescence such that the circuit is effectively open.
- **Pull-away:** the plated-through-hole copper or interface has separated from the surrounding board structure. Once that copper barrel starts peeling away from the fiberglass/laminate, the via or pin connection is no longer well supported. That can cause intermittent electrical contact at first, then full open-circuit failure, and it also makes the region much more vulnerable to thermal cycling and vibration.
- **Non-wetting:** molten solder failed to metallurgically bond to the substrate surface, typically due to oxidation, contamination, or insufficient flux activity. The result is a connection that may be present visually, but is weak, poorly adhered, and more likely to fail electrically or mechanically.

Experience shows how varied those defects can be in real hardware. In one connector study, Covalent observed significant voiding during X-ray inspection. However, mechanical cross sectioning was required to fully evaluate the failure.

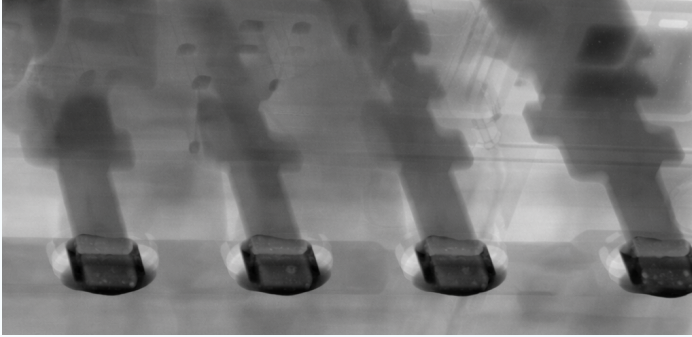


Figure 23: X-ray images of PCB components with voids.

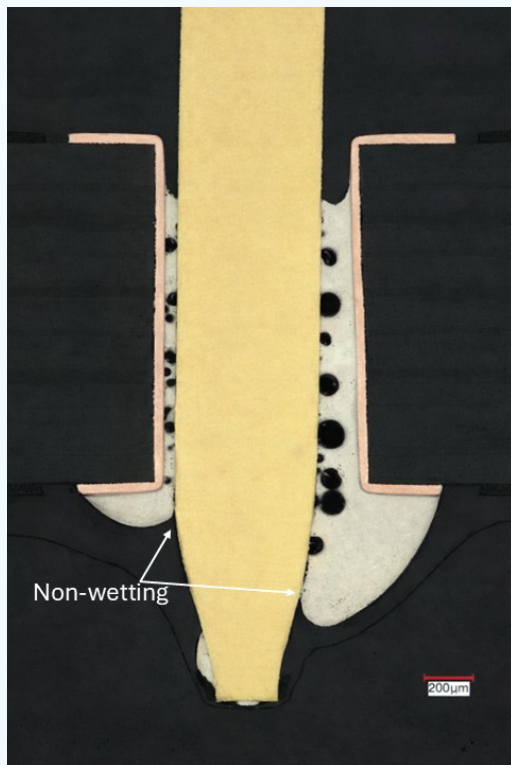


Figure 24: Optical microscopy image of the PCB pin component with non-wetting areas annotated.

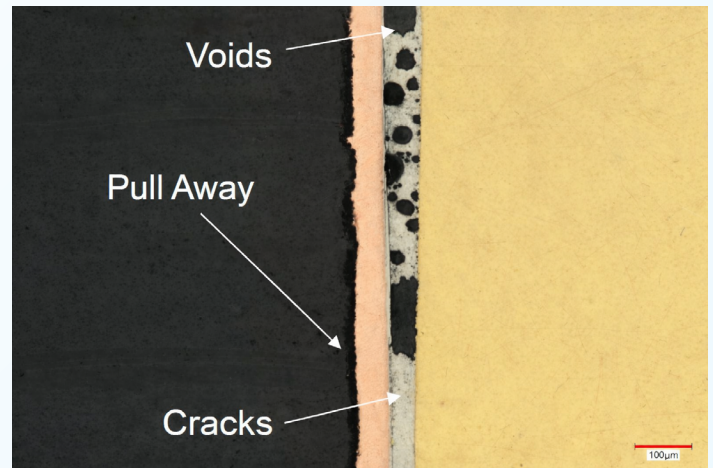


Figure 25: Close-up of pin with voids, cracks, and pull away annotated.

In this example, pull-away loosens the connection, cracks split the connection, and voids weaken the solder structure from the inside. When those occur in the same plated-through-hole or solder joint, the PCB can fail electrically, mechanically, or both. In other words, the issue is often not simply “there is solder here” or “there is no solder here.” The real issue is usually whether the solder bonded the way it needed to.

The analyst is trying to answer a similar kind of question as in metallurgical weld work: Did the interfaces form the way they were supposed to, and if not, where did that breakdown occur?

Welds and solder joints may both be “joints,” but they fail according to different logic. A weld fails when structural continuity is compromised—by defects like incomplete penetration, porosity, lack of fusion, cracking, crater-related crack initiation, or unfavorable microstructure (e.g., excessive grain growth, sensitization, or hydrogen embrittlement). A solder joint fails when electrical and interfacial reliability are compromised—by non-wetting, voiding, delamination, brittle separation, contamination,

plating issues, or defects in the board or component structure around the joint.

That distinction also explains why the workflow is different. In metallurgical work, the analysis often centers on the weld shape, penetration, microstructure, fracture behavior, and process parameters that created the joint. In PCB and electronics work, the analysis often centers on hidden interfaces, internal discontinuities, board construction, and the relationship between solder, plating, component metallurgy, and assembly conditions. Both are failure analysis, but they are not interchangeable versions of the same investigation. They require different questions, different expectations, and often different tools.

Covalent's FA team does not just document that a joint looks bad. We help determine what kind of joint it is, what that joint was supposed to do, how it failed, and what evidence is needed to connect the visible symptom to the true mechanism. Once that distinction is clear, the rest of the investigation becomes much more focused.

Context Matters: Data Center Infrastructure vs. Space Systems

Failure analysis does not happen in a vacuum. The same types of defects—cracks, voids, delamination, non-wetting, contamination—appear across industries. What changes is the context in which those defects occur, and that context fundamentally shapes how failures are investigated, interpreted, and acted upon.

Two of the most demanding environments for modern electronics are data center infrastructure and space systems. At first glance, these applications may seem different. In practice, they share important similarities—and

critical differences—that define how failure analysis is performed.

Shared Challenges: Large, Complex, High-Demand Assemblies

At a physical level, large PCB assemblies used in both data centers and space systems have a great deal in common. These systems rely on large, high-layer-count boards populated with dense arrays of components, including BGAs, connectors, and high-speed interconnects. Advanced packaging structures such as microvias and plated through holes are common, and performance requirements—both electrical and thermal—are demanding.

From a failure analysis perspective, the same core questions apply across both environments:

- Did the solder joints form correctly and reliably?
- Are plated-through-holes and microvias structurally sound and electrically continuous?
- Is there delamination or separation at critical interfaces?
- Are observed defects isolated, or do they reflect a broader process issue?

The same analytical workflows described throughout this eBook—visual inspection, X-ray, micro-CT, scanning acoustic microscopy (SAM), cross-sectioning, and SEM/EDS—are directly applicable in both domains. These techniques are designed to uncover hidden defects, resolve internal structures, and connect visible symptoms to underlying mechanisms.

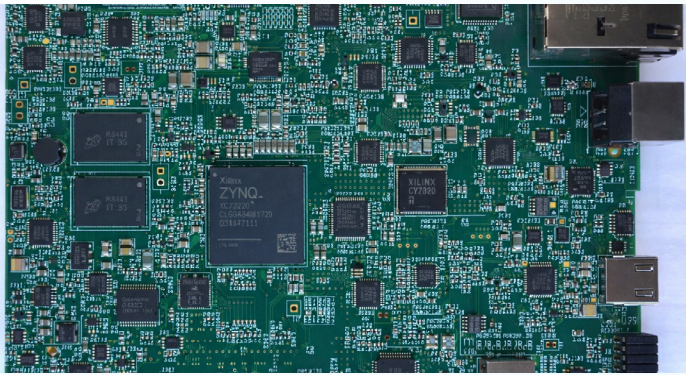


Figure 26: A large PCB assembly for data centers and space applications.

Diverging Priorities: Reliability vs. Speed

While the physical structures and defect types may be similar, the engineering priorities in these two environments are fundamentally different.

In space systems, failure carries potentially catastrophic and irreversible consequences. Hardware must survive for years in extreme conditions, often without the possibility of repair or replacement. As a result, manufacturing and qualification processes are slow, deliberate, and heavily guided by standards such as IPC and aerospace specifications. Extensive testing is performed before deployment, and failure analysis is used primarily as a tool for risk elimination and validation. The goal is to ensure that known failure mechanisms are fully understood and mitigated before the system ever leaves the ground.

In contrast, data center hardware operates under intense pressure to scale. Demand is high, timelines are compressed, and production often begins before processes are fully optimized. In this environment, failure analysis becomes a real-time problem-solving tool rather than a purely preventative one. Issues are frequently

identified during ramp-up or after deployment, and the priority shifts to rapid diagnosis and correction.

Instead of asking, “How do we ensure this never fails?”, the more immediate question becomes, “Why is this failing now, and how quickly can we fix it?”

Implications for Failure Analysis Workflows

This shift in priorities changes how failure analysis is applied.

In high-reliability environments like space systems, the emphasis is on completeness and confidence. Investigations are thorough, documentation is rigorous, and conclusions must be defensible upon a thorough review. The focus is on eliminating uncertainty and validating that design and process will perform reliably over years of service.

In data center environments, speed and scalability are equally critical. Analysts must move quickly from symptom to root cause, often across multiple samples or builds. Correlative workflows become essential because no single technique provides a complete picture. Non-destructive methods are used to rapidly screen and localize defects, while targeted destructive analysis confirms the mechanism and enables actionable recommendations.

In this setting, failure analysis is not just about understanding a single failure. It is about stabilizing a process, improving yield, and reducing risk across large production volumes.

The Role of Correlative, Multi-Technique Analysis

These demands highlight the importance of a flexible, multi-technique approach.

At Covalent, failure analysis workflows are designed to adapt to both environments. Non-destructive techniques such as X-ray, micro-CT, and SAM are used to quickly identify suspect regions and preserve critical evidence. Destructive methods such as cross-sectioning, parallel lapping, and dye-and-pry are then applied in a targeted way to expose the true interfaces and failure planes. High-resolution imaging and chemical analysis using SEM/EDS provide the final level of detail needed to confirm the root cause.

This approach allows investigations to scale from single-point failures to broader process-level insights. In a data center context, which means identifying systemic issues that may affect many boards. In a space context, it supports the deep validation required to ensure long-term reliability.

A Common Foundation: Materials, Processes, and Interfaces

Despite the differences in pace and philosophy, both environments ultimately depend on the same fundamentals. Materials selection, PCB fabrication quality, packaging integrity, and interconnect reliability all play central roles in determining performance.

Failure analysis bridges these domains by connecting observed defects to the underlying materials and processes that created them. Whether the goal is to prevent a failure in orbit or resolve a reliability issue in a high-volume production environment, the core task remains the same: identify the mechanism, understand the contributing factors, and provide data that supports the next decision.

In that sense, the value of failure analysis is not just in explaining what went wrong. It is

in enabling better outcomes—faster in some cases, and more certain in others—depending on what the application demands.

A Note on Chip and Die Level Failure Analysis

While this eBook has focused primarily on welds, PCB assemblies, and system-level failures, it is important to recognize that many failures originate at an even smaller scale—within the semiconductor device itself.

Chip- and die-level failure analysis follows a different, highly specialized workflow. Rather than starting with visible structural defects, these investigations often begin with fault isolation, where electrical or optical techniques are used to localize the failing region within the device. From there, the process typically moves into deprocessing, where layers of the device are selectively removed to expose the structures of interest. At the most advanced stage, techniques such as FIB cross-sectioning and TEM analysis are used to examine nanoscale features including interconnects, interfaces, thin oxides, and localized damage mechanisms.

This type of work is essential for understanding failures in advanced semiconductor devices, particularly where issues such as electromigration, dielectric breakdown, contamination, or process-induced defects may be involved. It is also a well-established discipline, and many internal and specialized external labs are highly optimized for this style of analysis.

At Covalent, we support chip- and die-level investigations when they are required, particularly when they are part of a broader failure analysis effort.

Conclusion: What Really Failed— and What Comes Next

Failure is rarely where it first appears. What looks like a crack, a void, or an open connection is usually the final result of a deeper issue rooted in materials, process, design, or environment.

Across welds, PCBs, and complex assemblies, the pattern is consistent. Craters lead to cracking, voids reduce strength, incomplete bonding creates weak interfaces, and small defects grow into real failures over time. Whether it's weld porosity acting as a stress concentrator or a shrinkage void initiating fracture in a casting, failures are rarely random—they are predictable when you understand the mechanism.

That's the role of failure analysis.

At Covalent, failure analysis is not just about identifying defects—it's about building a clear, defensible understanding of root cause. That means combining

non-destructive techniques with targeted destructive methods, then using chemistry and microstructure to complete the picture. No single tool provides the answer, but the right combination turns uncertainty into insight.

And that insight is what matters.

Because the goal is not just to explain what failed. It's to enable better decisions—improving processes, refining designs, and preventing the next failure before it happens. In fast-moving industries where reliability and speed both matter, that ability is not just helpful. It's essential. A complete failure analysis closes the loop and Covalent stays engaged through the process.

When something fails, the real question isn't just what broke? It's: What really failed—and what are you going to do about it?



Talk to an expert about your Failure Analysis needs.

Contact Us

Appendix A: Failure Analysis Techniques Reference Guide

Technique	What it helps answer	When it is used in failure analysis	Example use case
FIB (Focused Ion Beam)	Where exactly is the defect, and what does a highly targeted cross-section reveal?	Used when the area of interest is very small, buried, or difficult to reach with conventional cross-sectioning. Also useful for site-specific sample prep.	Preparing a targeted cross-section through a cracked microvia, voided solder interface, or buried defect in a semiconductor structure.
Nanoprobng	Is the feature electrically active, open, shorted, or resistive at a very specific location?	Used when the failure must be correlated with localized electrical behavior inside the microscope.	Probing a suspect trace, contact, or device node to determine whether a visible defect is actually causing the electrical failure.
TEM (Transmission Electron Microscopy)	What is happening at the nanoscale in the interface, microstructure, or damage layer?	Used when SEM is not enough and the problem depends on very fine structure, thin oxides, intermetallics, or nanoscale cracking.	Confirming oxide at a cracked copper-plating interface, examining intermetallic formation, or studying thin contamination layers.
XPS (X-ray Photoelectron Spectroscopy)	What chemistry is present on the surface, especially oxides, contamination, or thin films?	Used when surface chemistry matters more than bulk composition, especially in wetting, adhesion, or contamination-related failures.	Determining whether oxidation or organic residue on a pin, pad, or bond surface contributed to non-wetting or adhesion loss.
LECO / Combustion Analysis	What are the bulk light-element levels, such as carbon, sulfur, oxygen, or nitrogen?	Used when trace bulk chemistry may affect weld quality, embrittlement, corrosion, or alloy behavior.	Checking sulfur or oxygen levels in a metal sample to investigate cracking, brittleness, or unexpected weld behavior.

Technique	What it helps answer	When it is used in failure analysis	Example use case
ICP-OES / ICP-MS	Does the elemental composition match spec, and are trace elements or contaminants present?	Used when precise elemental analysis is needed, especially for alloys, coatings, contamination, or trace metals.	Confirming whether a metal part matches the claimed alloy, or identifying trace contamination that may contribute to corrosion or failure.
Cryo BIB (Cryogenic Broad Ion Beam)	Can we expose a clean cross-section in a soft, fragile, or heat-sensitive material without smearing or damage?	Used when conventional polishing would distort the structure, especially in polymers, soft interfaces, batteries, composites, or delicate electronics materials.	Cross-sectioning a polymer-rich interface, adhesive bondline, or soft layered material while preserving the true defect morphology.
IPC Testing / IPC Criteria Review	Does the assembly meet industry workmanship and acceptability criteria?	Used in PCB and electronics work to compare observed conditions against accepted manufacturing/reliability standards.	Evaluating whether solder fill, voiding, wetting, or other PCB features fall within IPC acceptance limits.
SEM/EDS	What does the defect look like at high magnification, and what elements are present there?	Used after visual inspection or cross-sectioning when morphology and local composition need to be confirmed.	Examining a solder crack, contamination on a connector pin, plating separation, or inclusions in a weld.
Optical Microscopy / Cross-Sectioning	What is the internal geometry of the joint, interface, or structure?	Used as a core destructive technique for welds, solder joints, plated-through-holes, capacitor terminations, and fractures.	Revealing incomplete penetration in a weld, pull-away in a plated-through-hole, or delamination in a capacitor termination.

Technique	What it helps answer	When it is used in failure analysis	Example use case
X-ray / microCT	Are there hidden internal defects, and where are they located?	Used early in the workflow for non-destructive inspection of buried features.	Finding voids in solder joints, hidden structural anomalies, internal separations, or suspect regions before destructive sectioning.
SAM (Scanning Acoustic Microscopy)	Are there delaminations, separations, or crack-like air gaps inside a layered structure?	Used mainly for electronic packages and PCBAs when interface separation is suspected.	Detecting delamination under components, inside packages, or in layered PCB structures.
Dye and Pry	Did a crack already exist in the solder joint before the component was removed?	Used for hidden solder-joint reliability issues, especially under area-array packages.	Identifying pre-existing cracks or head-in-pillow type failures in BGA-style interconnects.
Metallography / Etching	What does the weld microstructure look like, and how did the metal solidify or transform?	Used in metallurgical FA when grain structure, fusion, heat-affected zones, or microstructural anomalies matter.	Revealing weld penetration, fusion boundaries, grain structure, and crack paths in aluminum, steel, or titanium welds.
Fractography	Where did the fracture start, and how did it propagate?	Used when a part has cracked or broken and the failure mode must be reconstructed.	Determining whether a casting fracture initiated at a shrinkage void, or whether a ceramic or metal fracture was brittle, ductile, or fatigue-related.

Appendix B: Glossary of Failure Analysis Terms

Adhesion

The ability of two different materials to bond at their interface. Poor adhesion can lead to delamination or premature failure.

Brittle Fracture

A fracture that occurs with little to no plastic deformation, often propagating rapidly once initiated.

Crater (Weld)

A depression at the end of a weld bead formed during solidification. Craters can act as stress concentrators and are common sites for crack initiation.

Cross-Sectioning

A destructive preparation technique where a sample is cut, mounted, and polished to reveal internal structures and interfaces.

Delamination

The separation of bonded layers within a material or structure, typically caused by poor adhesion, thermal stress, or contamination.

Dye and Pry

A destructive method used to identify pre-existing cracks in solder joints by allowing dye to penetrate defects before mechanically separating the component.

Electromigration

The movement of metal atoms caused by high current density, which can lead to void formation and eventual electrical failure.

EOS (Electrical Overstress)

Damage caused when an electronic component experiences voltage, current, or power beyond its design limits. EOS can produce localized heating, melting, cracking, shorting, or other damage consistent with electrical failure.

Fractography

The study of fracture surfaces to determine where a crack initiated and how it propagated.

Fusion (Weld)

The complete melting and bonding of base materials during welding. Lack of fusion results in weak or incomplete joints.

Heat-Affected Zone (HAZ)

The region of base material adjacent to a weld that experiences microstructural changes due to heat but does not melt.

Head-in-Pillow (HiP)

A solder defect where the solder on the component and pad fail to fully coalesce, resulting in a weak or unreliable connection.

Hydrogen Embrittlement

A failure mechanism in which absorbed hydrogen reduces a metal's ductility and toughness, making it more likely to crack under stress. It is often associated with high-strength steels, plating processes, corrosion, welding, or hydrogen-containing environments.

Incomplete Penetration

A weld defect where the weld metal does not extend through the full joint thickness, leaving an unfused region.

Interfacial Separation

A failure mode where bonded materials separate at their interface.

Intermetallic Compound (IMC)

A compound formed between two metals, typically at an interface (such as solder and a pad). Thin IMC layers are necessary for bonding, but excessive growth can make the joint brittle.

Microvia

A small, typically laser-drilled via used in high-density PCBs to connect layers. Microvias are susceptible to cracking under thermal or mechanical stress.

Non-Wetting

A condition where molten solder fails to properly spread and bond to a metal surface, often due to oxidation or contamination.

Porosity

The presence of small voids or gas pockets within a material. In welds or solder joints, porosity can reduce strength and act as crack initiation sites.

Pull-Away

A failure mode where a plated-through-hole or interface separates from the surrounding material, leading to intermittent or open electrical connections.

Root Cause Analysis (RCA)

A structured process used to identify the underlying cause of a failure rather than just its symptoms.

Scanning Acoustic Microscopy (SAM)

A non-destructive technique that uses ultrasound to detect internal features such as delamination, voids, and cracks.

SCC (Stress Corrosion Cracking)

Crack growth caused by the combined action of tensile stress and a corrosive environment. SCC can produce brittle-looking cracks even when the applied stress is below the normal strength of the material.

Sensitization

A microstructural condition, especially in stainless steels, where chromium carbides form at grain boundaries after thermal exposure. This can deplete chromium near the grain boundaries and make the material more susceptible to intergranular corrosion or cracking.

Shrinkage Void

A void formed during solidification (commonly in cast materials) due to volume contraction, often acting as a stress concentrator.

Stress Concentrator

A feature such as a notch, crack, or void that locally increases stress and makes failure more likely.

Undercut (Weld)

A groove or reduction in thickness at the edge of a weld, which weakens the joint and promotes crack initiation.

Voiding (Solder)

The presence of trapped gas pockets within a solder joint, which can reduce mechanical and electrical reliability.

Wetting

The ability of molten solder to spread across and bond to a metal surface. Good wetting is critical for reliable electrical and mechanical connections.