Designing High-Reliability, High-Longevity Electronic Systems

Marc Stewart

Bigger Outlasts Smaller

The world of electronic products is dominated by smart phones and tablet computers where small, sleek, and sexy win the customer over. But as much as small is beautiful in consumer electronics, large and robust wins every time in applications where ruggedness and long life are paramount.

Big things simply outlast little things. For example, the pyramids of Giza have held up pretty well for being several thousand years old. The largest one—the Pyramid of Khufu (Cheops)—is in the best condition, even though it is the oldest. It's true in electronics also, particularly in solder joints. Large solder joints simply outlast small ones. As useful as solder is—indispensible, really—it does slowly crystallize and turn brittle, especially when exposed to mechanical stress cycling. Mechanical stress cycles can come from repeated shock and vibration, and from forces exerted by component leads or the circuit board against the solder.

Repeated temperature changes ("thermal cycling") activate these mechanical stressors, particularly in small solder joints such as are found on surface-mounted components. Damage accumulates with thermal cycles and accelerates with rapid temperature changes (thermal shock) and with wide temperature extremes.

"The grain structure of solder is inherently unstable. The grains will grow in size over time as the grain structure reduces the internal energy of a fine-grained structure. This grain growth process is enhanced by elevated temperatures as well as strain energy input during cyclic loading. The grain growth process is thus an indication of the accumulating fatigue damage. At the grain boundaries contaminants like lead oxides are concentrated; as the grains grow these contaminants are further concentrated at the grain boundaries, weakening these boundaries. After the consumption of ~25% of the fatigue life micro-voids can be found at the grain boundary intersections; these micro-voids grow into micro-cracks after ~40% of the fatigue life; these micro-cracks grow and coalesce into macro-cracks leading to total fracture as is schematically shown in Figure 1." (SOLDER JOINTS IN ELECTRONICS: DESIGN FOR RELIABILITY, Werner Engelmaier, Page 2)

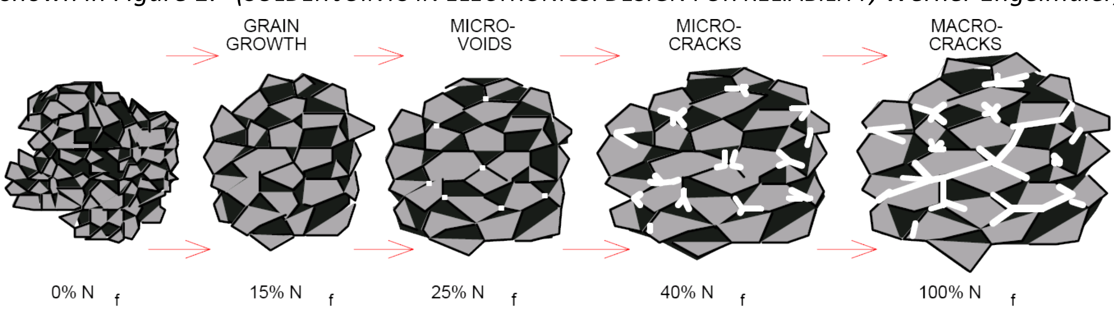

Figure 1: Depiction of the Effects of the Accumulating Fatigue Damage in Solder Joint Structure [1].

Solder failure due to work-stress fatigue from cyclic stress is the result of exponentially-compounding damage: damage that starts slowly and accelerates ever faster toward complete failure. On the way to complete failure, solder degrades both electrically and mechanically. It is not uncommon to find an overstressed solder joint reduced to powder by cyclic work-stress fatigue.

High-current solder joints, such as on solar cells, further accelerate solder joint destruction by electrical self-heating. Mechanical degradation in high-stress solder joints, also found on solar cells, further accelerates solder-joint destruction by forcing stress into ever-smaller surviving portions of the joint as failing portions fracture and lose capacity. Once enough of the solder has crystallized, the joint fails. The best way to mitigate this vulnerability is with volume: more solder is better. Just as the Great Pyramids have stood up against the sandstorms of time, so will a large-volume solder joint stand against time and thermal cycling. With larger volumes of solder, initial stress loading is over a wider area, reducing stress at any one point. Larger volumes of solder provide redundancy so that as sections fail, other undamaged areas can support the load.

Principle #1: Use Only Through-Hole Components

This need for large-volume solder joints places a rather severe limit on designs, because so many components are available only in packages too small to accommodate large solder joints. The best packages are the original-style dual in-line ("DIP") packages. They have leads spaced 0.1" on center, and are designed to be mounted in holes that go through the printed-circuit board so the solder joint is a barrel filled with solder, with the wire of the DIP lead going through it. This part type is categorized as through-hole technology (as opposed to surface-mount; see the next paragraph). The lead of the component helps strengthen the solder joint, much as steel rebar strengthens concrete. Because the component lead is long, the forces caused by thermal expansion of the part and board are spread out over the length of the lead, reducing the force applied to the solder. For ruggedness and long life, one cannot beat the advantages of through-hole parts. Because the solder joint between the lead and circuit board exists on both the top and bottom of the board, plated-through hole (PTH) interconnects are inherently redundant. The plated metal barrel in the hole electrically connects both the top solder joint and bottom solder joint to each other. This allows either top or bottom to completely fail with no impact on the circuit.

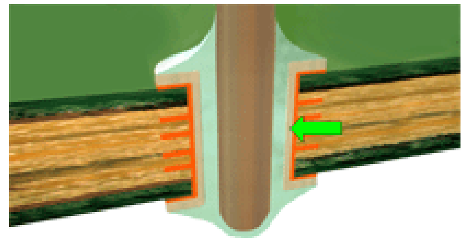

Fig 2 Lead in PTH

Consumer products are built almost exclusively with surface-mount parts (SMT – surface-mount technology). SMT components are either leadless or have short leads that sit on the surface of the PCB. SMT lead spacing starts at 0.050" and goes down from there, to 0.012" or even closer. The tighter spacing makes for much smaller parts, and therefore smaller products, but only at the cost of reduced ruggedness and shorter lifetime. The short leads of SMT components transmit many times the thermal expansion stress to a very tiny area of solder. The solder itself is much more highly stressed because it is both the electrical connection and the mechanical attachment for the component.

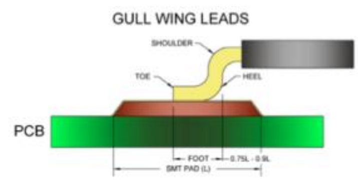

Fig 3 SMT Lead on surface

For products that rarely see extreme temperatures and are only expected to last a few years, that works well enough. But for products intended to spend decades outdoors, the only option is to go "old school" and work with through-hole parts. On average, a through-hole solder joint is about 10,000 times more reliable than even a large surface-mount joint. That component lead connecting the top of the board to the bottom makes a huge difference, and of course the volume of solder in a barrel is much higher than in a surface-mount joint.

Fig 4 SMT failure

So-called passive parts—resistors, capacitors, inductors, etc.—are available in larger surface-mount packages, so surface-mount passive parts can have larger-volume solder joints. But there are three problems, still: 1) the solder joint is still very small in volume compared to a through-hole joint; 2) there is no lead-in-barrel strength reinforcement; 3) the components themselves are subjected to thermal stresses and can fracture. Passive components should also be through-hole type.

Principle #2: Back Up Your Vias

The physical design of the printed circuit board itself has a major effect on overall reliability. With a design goal of zero single point to catastrophic failure, a failure mode effects analysis (FMEA) shows that a primary failure mode of a circuit board is the via. A via is a plated hole in the printed-circuit board (PCB). It carries a signal from one layer to another. Via fracture is rare and often overlooked, but because there can be 100s of vias, their cumulative effect on the failure rate can be significant. Via fracture is primarily caused by stresses due to different thermal expansion rates of the metal (primarily copper) and the fiberglass-epoxy substrate. Vias that have component leads through them with top and bottom solder joints (that is, through-holes for component leads) are already backed up by the wire connecting top to bottom. When it is practical that a via be large enough to fill with solder, the solder itself can reinforce the via, much as a wire would. Sometimes, vias must be too small to be filled; these are the

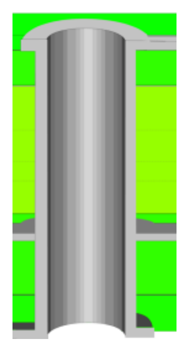

Fig 5
Via Cross-section

most vulnerable. For maximum reliability, all vias—large and small—should have back-ups: every time a signal crosses from one layer to another, it should do so through two or more redundant vias. In the rare case that one breaks, there is a spare to keep the signal intact. Via fractures are rare enough that a single back-up is sufficient. The idealPV FOZHS controller uses vias that are *both* redundant *and* solder-filled, for an extra margin of reliability.

Principle #3: Go Wide-Track

Modern printed-circuit manufacturing techniques allow for very skinny metal tracks, with equally skinny spaces between tracks. That's all well and good, but when you want a track to stand up over time and temperature cycling, wide tracks are the way to go. Consumer products are routinely built with tracks and spaces of 0.004" to 0.006", but industrial, outdoor products should be built with 0.010" tracks or larger. IdealPV's products are built with 0.012" minimum track width.

Principle #4: Eschew Electrolytic Capacitors

Electrolytic capacitors are low-cost alternative to tantalum, ceramic, film, etc., but they have limited life spans. An electrolytic capacitor uses a spiral-wound oxidized-aluminum sheet wrapped together with paper, placed in a metal can filled with a liquid very similar to dry cleaning fluid. A synthetic rubber plug (with two holes in it for lead wires) seals the contents of the can, but as you might guess, electrolytic capacitors tend to leak and boil off the liquid. Manufacturers make no bones about this fact, and even rate their electrolytic capacitors in terms of how long they will last at a given temperature. Ratings run anywhere from 2,000 hours at 85 °C to 10,000 hours at 125 °C, for the really high-reliability types. The best way to get more life out of an electrolytic capacitor is to keep its temperature down—each 10 °C reduction in temperature roughly doubles the lifetime—but even the best electrolytic capacitors will not hold up for 40 or more years outdoors. For idealPV designs, we just say "no" to electrolytic capacitors.

Fig 6
Leaking Electrolytic Capacitors

Principle #5: Keep It Cool

To keep circuit interconnects intact and components healthy, thermal extremes must be limited as much as possible. For circuit components especially, heat kills; not just electrolytic capacitors, but every silicon circuit also wears out faster at higher temperatures. The degradation comes from ion migration, which essentially "un-makes" a transistor or diode. In a transistor, leakage goes up ("off" starts to look more like "on") and gain goes down ("on" starts to look more like "off"). In a diode, which is essentially a one-way switch, the result is the same: "off" is less "off" and "on" is less "on." As the parts degrade, they start running hotter, which compounds the problem and speeds up eventual breakdown. The best defense is to keep things running cool at all times. Transistors may last tens of thousands of hours at a junction temperature (that's the temperature inside the case) of 150 °C, but will last millions of hours if kept below 100 °C. Proper thermal design is a must; a good technique is to design for junction temperature rises of no more than 20 °C above ambient; preferably 10 °C.

Silicon component degradation accelerates exponentially with temperature. For example, a solar cell rated for a 25 year life to 20% degradation at 25°C would likely reach its end-of-life level in about 220 hours under a partial shade induced hot spot that raised the cell temperature to 125°C. During the summer, solar production accumulates to 220 hours in less than a month. Hotspots can exceed 190°C, which could degrade the cell in less than three hours, if it the solder joint doesn't fail first.

Principle #6: Beware the Propagating Arc

Sometimes the unexpected happens: moisture or grit may to get in, or a power surge may occur, starting an arc. The key is to make sure the arc goes out before it travels too far. Direct-current (DC) arcs will not go out on their own, like AC arcs, so the board layout must force them to extinguish. The trick to quenching a DC arc is to direct its path toward an ever-widening gap. When the arc first strikes, it eats away some of the metal closest to it and migrates toward fresher metal nearby. After it chews a bit of that away, it moves toward more fresh metal. A gap that is shaped correctly will encourage the arc to propagate toward wider and wider spacing, until the space is too great for the arc to sustain itself. Long, parallel runs of metal with a DC voltage between them invites an arc to not only sustain itself, but to eat half the board away. A few strategically-placed gap-widenings can keep small sparks small and short-lived, preventing destructive damage to the board.

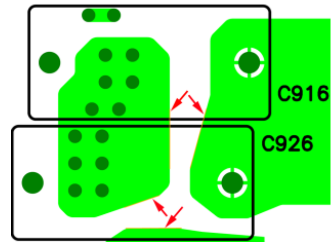

Fig 7 Arc-stopping Gaps