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How Lead-Free Changes Can Impact Reliability

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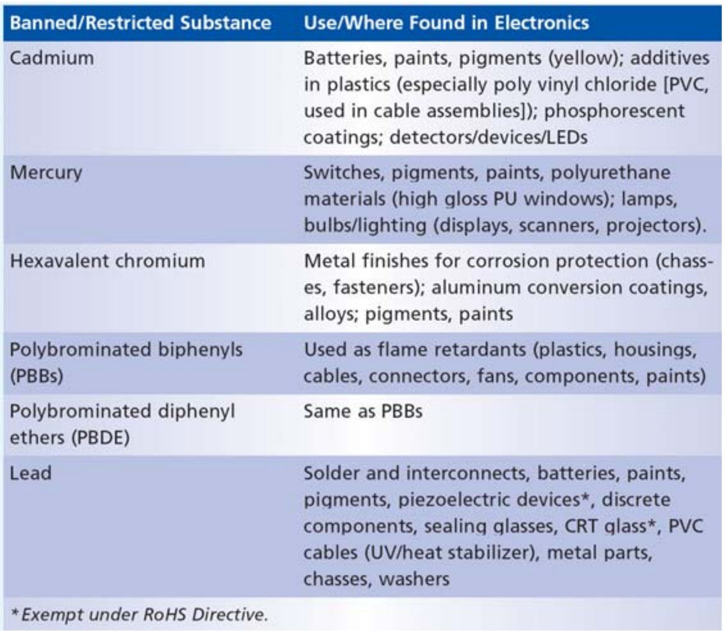
The Initial Problem

Anyone who's been paying attention knows that the governments are turning "green" – meaning they are banning "hazardous" substances. The European Union (EU) took the lead in this endeavor with a directive, "restriction on the use of certain hazardous substances in electrical and electronic equipment," or simply. "RoHS" This directive (with some exceptions) bans six substances from manufacturing products (Table 1) [1].

As this table indicates, use of one of those banned metals, tin, has turned the electronics manufacturing industry on its ear. China, Japan, and other countries are developing their own bans on lead and other substances, as well.

Table 1. Banned Substances based on the RoHS Directive



Banned/Restricted Substance	Use/Where Found in Electronics
Cadmium	Batteries, paints, pigments (yellow); additives in plastics (especially poly vinyl chloride [PVC, used in cable assemblies]); phosphorescent coatings; detectors/devices/LEDs
Mercury	Switches, pigments, paints, polyurethane materials (high gloss PU windows); lamps, bulbs/lighting (displays, scanners, projectors).
Hexavalent chromium	Metal finishes for corrosion protection (chasses, fasteners); aluminum conversion coatings, alloys; pigments, paints
Polybrominated biphenyls (PBBs)	Used as flame retardants (plastics, housings, cables, connectors, fans, components, paints)
Polybrominated diphenyl ethers (PBDE)	Same as PBBs
Lead	Solder and interconnects, batteries, paints, pigments, piezoelectric devices*, discrete components, sealing glasses, CRT glass*, PVC cables (UV/heat stabilizer), metal parts, chasses, washers

**Exempt under RoHS Directive.*

Since the '60s we've know of a phenomenon called "tin whiskers." This artifact appears when tin is present in pure enough form to result in conductive outgrowths or "whiskers." These whiskers are conductive, so over time they can result in short circuits in otherwise reliable circuits. This is a particularly knotty problem in the electronics industry now, because for decades it has depended on tin-lead solder to attach ever-shrinking components on to very dense printed circuit cards. However, without the lead in the solder to metallurgically bond with the tin in the solder, the tin goes back to its old habit – growing whiskers. This goes for finishes, too. Care must be taken to assure a high-percentage tin is not on the lead finishes. If tin is there, whiskers can form there, as well.

The Problem with the Solutions

One of the unintended consequences of trying to solve this issue is that the industry has had to turn to new materials and methods for attaching parts to boards. This comes at a time when the semiconductor industry is devising new ways to package their integrated circuits (ICs) to crowd continuously smaller geometries into them and at the same time introduce smaller logic voltages and tinier lead spacing to accommodate the high speeds and increased computing power the market is demanding. So now this “growth problem” is complicated by using new attachment technologies, trying to avoid the known tin-whisker problem. Some of these possible techniques include:

- New metal combinations for solder with different melting;
- Refinishing the package leads (for industries in which tin is allowed); and
- Coating the devices to help mitigate the whisker risks. This has its own set of problems – little or no test data that verify the coatings will work, and configurations like ball grid arrays (BGAs) that make coating in the inner connections difficult, if not impossible.

Another issue associated with this tin-whisker phenomenon is that it is not well understood. For that matter neither are the potential “improvement” techniques. Part of that concern is tied to the fact that tin whiskers can take years to appear. This is compounded by the fact that the *cause(s)* of the whisker phenomenon is not well-understood. Since there is not a lot known about the formation of whiskers, there is not a good way right now to perform accelerated testing. The impact of this issue varies from segment to segment in the industry. For instance, the mobile telephone segment may not need to worry as much for phones that won’t last many years, but the automotive, defense, space, and other segments that have products that are expected to last many years, whiskers is a problem. True, in some cases the military designs have some exemptions (or did have them). However, with the industry being driven to lead-free, the tin-lead products and solders are becoming scarce. …And those telecom guys? They’re not off the hook, either. Since new attachment and packaging techniques are being devised, their equipment must be able to withstand the higher reflow temperatures that are tied to lead-free solders, and they still can’t assume the new materials are adequate. They still must survive the use and abuse by their customers.

So, What Do We Do? Where IS that Masked Man?

All is not “gloom and doom.” Although there is no “Lone Ranger” who will single-handedly save us from this problem, there are many companies and organizations working to develop not only new techniques, but test them to understand their strengths and weaknesses – to verify they are not “catastrophic improvements.”

Examples of such efforts under way:

- **The study of tin whisker bridging on compressive contact connectors[2]:** A scanning electron microscope was used to measure tin whisker length, direction, origin location,

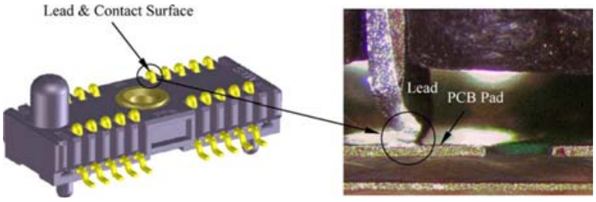


Figure 1. Compressive Contact Connector

and count. This data was used to develop a failure probability model. The researchers found that 74% of the observed whiskers would fail National Electronics Manufacturing Initiative (NEMI) criteria for length in about a year, but based on probability modeling, only about 0.0074% of those whiskers would actually cause bridging in that year. Refer to Figure 2, below.

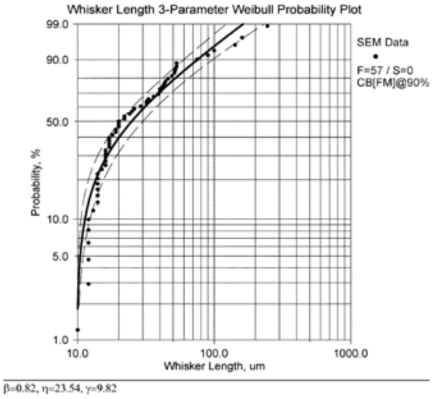


Figure 2. Whisker length probability Plot

This is an interesting observation, because the fact that whiskers are present does not mean that a cause will result. As mentioned above, the impact of the whiskers depends on condition, composition and configuration of the solder, and time. If the product isn’t intended for use over decades, then viewing its main life over a one or five-year period is useful.

Another observation was that the count of whiskers tended to fit a Poisson probability distribution. This combined with data about the location and direction of the whiskers, then allowed the model of the failure probability to be created.

- **The assessment of the reliability and quality of reballed plastic ball grid arrays (BGAs)[3]:** In responding to the lead-free directives, manufacturers with exemptions are experiencing a shortage of BGA parts with tin-lead materials. Reballing may be an option to replace the lead-free balls with tin-lead, if the reliability and quality of the end-product is not compromised.

  The two steps – solder ball removal and solder ball re-attachment – must both be evaluated in terms of the end result. The reliability and quality of the resultant package’s BGAs. To evaluate the reballed BGA robustness, attach strength was used. Two methods to evaluate this strength are: solder ball attach strength (shearing each ball from the body to measure the shear force required) and cold ball pull (CBP) test (pulling the ball at low temperature to measure the tensile force required). In this evaluation, both of these methods were used with two ball removal and two ball replacement processes for comparison.

  The two removal processes were:

  - Solder Wick (Figure 3): In the solder wick process, a soldering iron heats a copper braid, which is manually wiped over solder ball. The braid wire melts the solder balls and adheres to the molten solder.

Figure 3. Solder Wicking

- Low Temperature Wave Solder (Figure 4): In this process, the component suspended in a solder wave for a sufficient time to remove the solder balls. The solder in the wave is eutectic tin-lead.

Figure 4. Low-Temperature Wave Solder

The "virgin" BGAs without reballing and the reballed BGAs were compared (Figure 5) with and without aging exposure. These "Box plots" (that display upper and lower extremes, the mean and standard deviation for each data set) indicate the non-reballed BGAs exhibited higher shear strength than the reballed BGAs. This finding was consistent two types of packages and was independent of the reballing technique used.

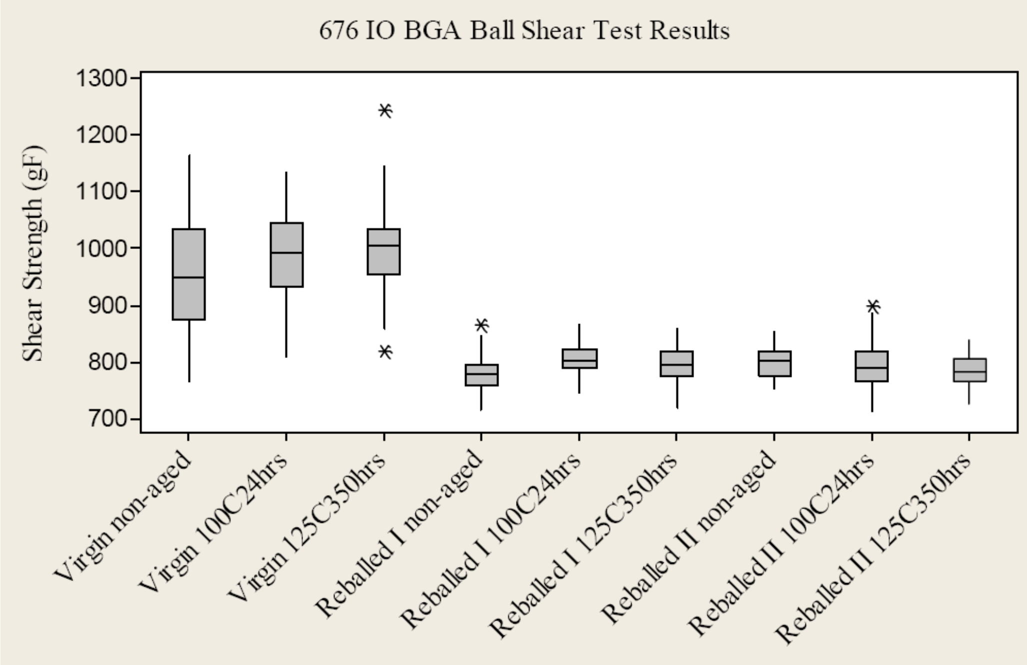


Figure 5. Shear strength Box Plots for non-reballed and reballed BGAs

Failure analysis of the balls that underwent the destructive ball shear test indicated that all displayed ductile failure (the fracture was within the bulk solder). The failure sites showed that, as would be expected, the tin lead solder was softer than the lead free (tin-silver-copper, SnAgCu, or "SAC," solder).

The cold bump pull (CBP) test was also performed on a sample of virgin and reballed BGAs (Figure 6). Similarly, virgin and reballed were compared with and without exposure to aging environments. These tests also showed a higher strength for the non-reballed over the reballed BGAs. This was true for a high pull rate (5000 µm/s) and a low rate (500 µm/s).

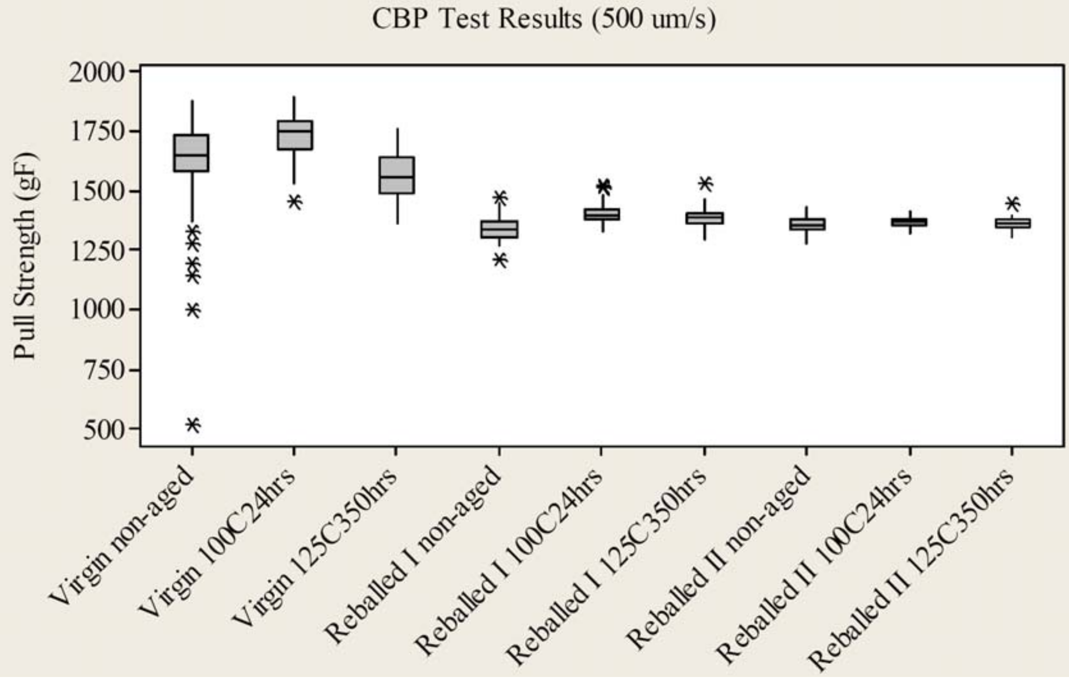


Figure 6. Pull Strength of Non-Reballed and Reballed BGAs

In this testing, the reballed failures occurred within the solder ball, itself. The non-reballed failures were a mix of failures associated with the ball (as with the reballed sample), as well as the bond, the pad, and the ball extrusion.
The conclusions drawn were:

- There was no correlation with the process used in reballing.
- Aging does not greatly influence the interconnect strength of the tin-lead solder after reballing.
- Non-reballed lead-free solder balls were found to have greater strength and a wider statistical distribution than the reballed tin-lead samples.

- **The Effects of Mechanical Shock on the Reliability of Solder Joint Adhesion [4]**
  This study focused on two areas – the effectiveness of different board level adhesive technologies, and the identification of key attributes to optimize adhesive geometry. Although mechanical shock resistance was a key parameter, the cost effectiveness of the adhesive method was also considered. There were three categories of board-level adhesive methodologies evaluated: full underfill (FF), partial underfill at package corner

(CF), and corner glue (CG). Assembled packages were tested to failure with increasing shock levels to serve as a performance indicator.

The handheld sector has driven the use of underfill and partial underfill to mitigate drop risks in the field. The evolution of this technique includes full underfill, underfill at corners, board-level adhesive, and mixtures of full underfill with corner glue. Interestingly, the use of underfill is used for flip chip, as well as BGA technologies. However, the underfill serves two different purposes for these package types. Flip chip underfill helps to mitigate issues associated with coefficient of thermal expansion (CTE) difference, especially problematic when exposed to thermal cycling. However, board-level underfill helps to provide mechanical shock protection.

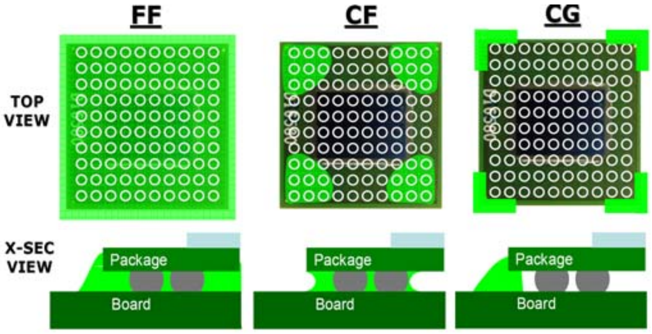


Figure 7. Adhesive types that underwent mechanical shock testing

Results – Adhesive Type

- The full underfill (FF), corner underfill (CF), and corner glue (CG) underwent shock testing.
- For the FF and CG adhesive types, no open was detected after shock exposure. In failure analysis, minor cracks were observed in CG, but none were detected with the FF.
- However, since the CG still provides sufficient margin and provides ease of rework, as well as uses less material, further studies were focused on the CG adhesive type.

Results – Fillet Geometry

- Since the corner-glue (CG) method is frequently manually dispensed, the study focused on variations in the manufacturing environment.
- Fillet height, width, and coverage were included in a finite-element analysis (FEM).to predict mechanical shock protection of the CG method. In particular, fillet height was modeled with respect to CG stresses, where the lower the force shown, the better the protection for the package. Figure 8 shows the FEM results – that CG stress for a given shock is inversely proportional to the fillet height (at least between 10-70% of the side wall of the package).
- Also, fillet width (the distance from the external to the internal glue footprint) was important. The FEM indicated the wider the fillet width, the smaller the glue stress. It was also found that there is better protection if the fillet covers the first three rows of a BGA package, but the advantage tapers off beyond those first three.
- The FEM models were verified with empirical data collection. Five configurations with different fillet geometries were tested, showing that indeed the fillet height and width were the most significant factors.

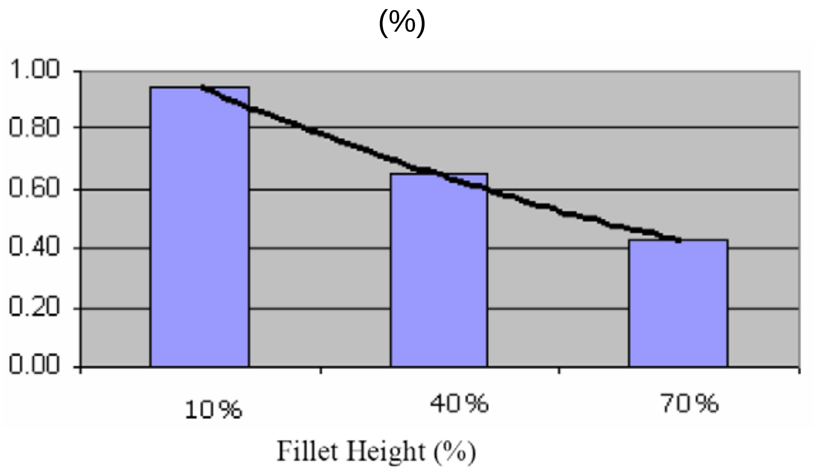


Figure 8. Normalized Glue Stress vs. Fillet Height

The study concluded that using CG seems to be the most cost effective attach method. The key attributes is the fillet should be a continuous application with >1mm wide, >50% height up the wall of the component, and >3 ball rows deep.

What Else?

The above examples of tests and study are under way in many companies, organizations, universities and other laboratories. The findings they are publishing means that there is and will be progress towards having known processes, materials, and standards to guide the manufacture of lead-free products. With this emphasis on such reliability testing, it would not be surprising if the industry ended up with higher reliability attachment methods for the new high density designs and applications in the electronics industry. There will still be a mystery involved in the testing to verify tin-whisker fixes for quite awhile. Without conclusive knowledge of what drives these whiskers, “accelerated testing” could be confounded. Even the Lone Ranger doesn’t have a silver bullet for this one.

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