Bead Probes in Practice

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Abstract

Bead Probes, a technology for In-Circuit Test probing of high-speed and/or high-density printed circuit boards was introduced at the 2004 International Test Conference [Park04]. Since then much experimentation has been done with Bead Probe technology, and a large, high-density board has been designed and produced that makes use of them. This paper discusses the learnings from these efforts.

1 A Short Review of Bead Probes

A Bead Probe is a very small hemi-ellipsoid structure made of solder. This bead typically lies on top of a signal trace, aligned to its width and following the trace for 4 to 6 times its width. This bead would be only a few mils tall, clearing the surrounding solder mask by several mils. Beads are made with standard solder paste/reflow processes in parallel with other solder features.

1.1 The Bead Probe and Fixtured Target

End and side sectional views of a solder bead are shown in Figure 1. The size and shape of the bead is determined by the volume of solder, the area of exposed copper and surface tension while it is molten during reflow.

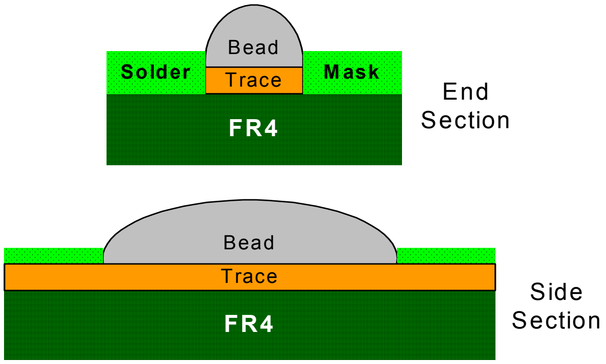

Figure 1: End and side sectional views of a bead probe.

The bead protrudes above the solder mask that is typically only a mil or two thick. When the fixture is activated, bringing the board into contact with the fixture, the probe targets situated in the fixture contact the bead probes. The spring-loaded fixture target probes are round and flat-faced, like those we often use for probing pointed objects such as through-hole pins. See Figure 2.

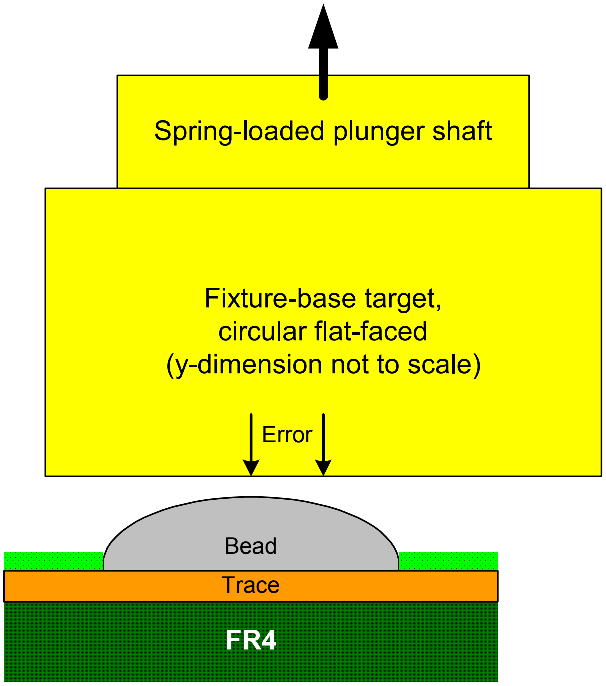

Figure 2: Side view of bead probe and target.

Note that the inevitable registration errors become lateral translation errors, where the bead probe and the target are not perfectly centered. The errors that occur are the same we have been handling for many years.

1.2 Fabricating a Bead Probe

A bead probe is manufactured using the same paste and reflow steps that other solder features follow, at the same time. The solder mask is opened up over the trace where we want a bead. A carefully engineered volume of solder paste is applied. When solder reflows and then freezes, it will wick up onto the copper trace due to the affinity of solder for copper and lack of affinity for the mask. At this scale, surface tension will completely overwhelm gravity, causing the bead to have a curved surface. The solder mask opening defines the outside dimensions of the bead.

The height of the bead is controlled by two factors. First, by volume, a typical solder paste is roughly 50% flux, which will vaporize during reflow. Thus roughly ½ the volume of paste will remain as solder. The solder stencil aperture is sized to assure that enough solder is deposited to later "bead up" via surface tension to a height that exceeds the surrounding mask. An example stack up of trace outline, solder mask and stencil holes is shown in Figure 3.

The solder mask hole is an obround hole (rectangular with rounded ends) of width W and length L center to center as shown. The width should be equal to or less than the width of the trace. The length should run in the same direction as the trace. The area of the obround hole, which exposes copper, is $WL + \pi(W/2)^2$.

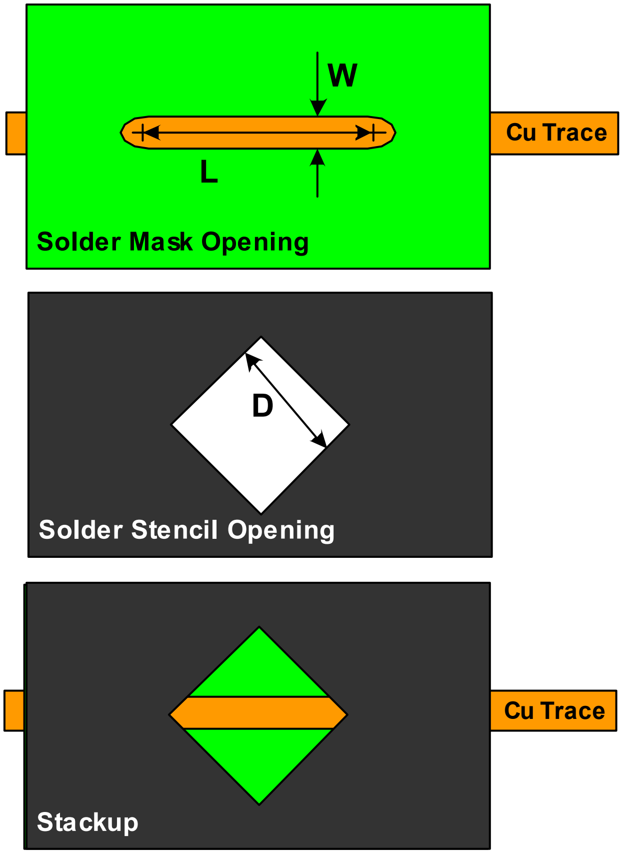

Figure 3: Board, solder mask and solder stencil layer stack up for a bead probe.

The solder stencil hole is a square (side length D) rotated 45 degrees to the trace and centered on the bead location. This hole is larger in area, D^2, than the mask hole. The rotation maximizes the area of copper that will receive solder paste, while the square is a preferred geometry for reliable stenciling. Some paste will be applied to the solder mask, but this paste will flow onto the copper when melting. The thickness T of the stencil will also determine the amount of solder paste that is applied. The paste volume applied to the board will be TD^2, which after vaporizing the flux will yield $TD^2/2$ volume of solder.

Given W, L, D and T, we can calculate the approximate height H of the resulting bead as follows. Divide the solder volume by the exposed copper area, or:

$$H \approx (TD^2/2) / (WL + \pi(W/2)^2)$$

If we are given W, H, D and T, then we can calculate the approximate length of the bead as:

$$L \approx ((T*D^2/2) / (H *W)) - \pi W/4$$

2 Theory of Operation

Traditional ICT bed-of-nails probing works by using sharp pointed fixture probes to hit targets on a board. Consider a spear-shaped probe contacting a solder-covered target. The spring-force of the probe will force the sharp point into the solder for some distance. This distance is governed by the spring force and the yield strength of solder. Yield strength for solder (leaded and lead-free) is about 5000 pounds per square inch.

As the spear point first touches the solder and any oxide or contaminants on its surface, the area of the point is not large enough to support the spring force, causing the solder to yield. The point of the probe begins to enter the solder, displacing any oxide or contaminants. At the probe tip continues to enter the solder, it has an increasing cross-sectional contact area. At some time this area will be large enough to support the spring force, and the probe no longer displaces solder so the probe does not travel any further into the solder.

Bead probes also show displacement of solder when contacted by a flat-faced fixture target probe. They get a flattened head as shown in Figure 4. This flattening displaces oxide and contaminants and provides good electrical conductivity.

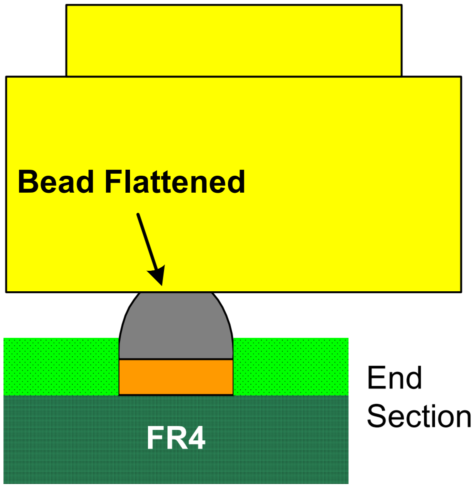

Figure 4: A bead probe flattens when contacted.

Beads are (approximate) hemi-ellipsoidal structures. When a hard, flat surface is pressed onto them, the initial contact is a point with infinite pressure, so the solder must move. As the surface yields, an area begins to form which is basically an ellipse with a semi-major axis A that runs along the length of the bead, and a semi-minor axis B that runs along the width. The area of the ellipse is πAB. The area continues to increase until it is able to support the spring force. Using the yield strength of solder expressed in ounces per square mil (0.08), we see the areas needed to support a force in Table 1. The semi-minor axis of a bead is often constrained to the width of the trace it sits upon. If a bead is too small, the surface area needed to support the spring force might be larger than the bead itself, implying that the bead would be catastrophically crushed out over the solder mask. If the bead is overly large, then the surface yield area may not displace enough solder to move oxides.

Probe spring force (oz)	Area to support force (mil^2)
2	25
4	50
8	100

Table 1: Surface area needed to support various probe spring forces.

The semi-minor axis should not exceed 50% of W (W > 2B) as shown in Figure 5 as this would imply bead crushing.

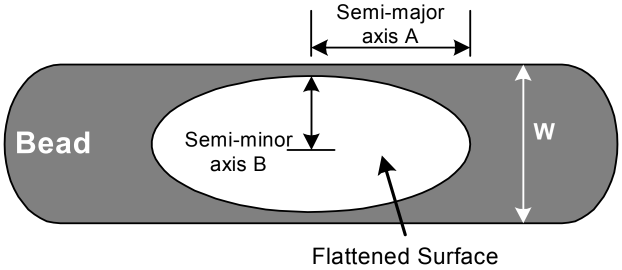

Figure 5: Top view of a flattened bead.

Table 2 shows semi-major axis lengths needed to support spring forces for some bead widths and forces. For low spring forces, beads must be very small or there will not be much surface yield on the bead. For all beads, the semi-major axis must be smaller than ½ length of the bead, as was true for the semi-minor axis versus width. Again, using the 50% factor, each bead length should be greater than 2 times the semi-major axis length (L >2A).

Spring Force (oz)	Bead Width (mils)	Semi-minor axis B (mils)	Semi-major axis A (mils)
2	3	1.5	5.3
	4	2	4
	5	2.5	3.2
4	4	2	8
	6	3	5.3
	8	4	4
8	4	2	16
	6	3	10.6
	8	4	8

Table 2: Bead design parameters for various probe spring forces.

Figure 6 shows a newly minted bead in cross section, mounted on a 4 mil wide trace. There is flux residue (no-clean process) pooled up against the sides of the bead. The trace itself shows classic over-etching of its sides and a Copper-Nickel-Gold plated cap. At this point in the sectioning, the bead was 2.9 mils tall. Other sections of the same bead had heights ranging from 2.3 to 3.7 mils. The width stayed fairly constant.

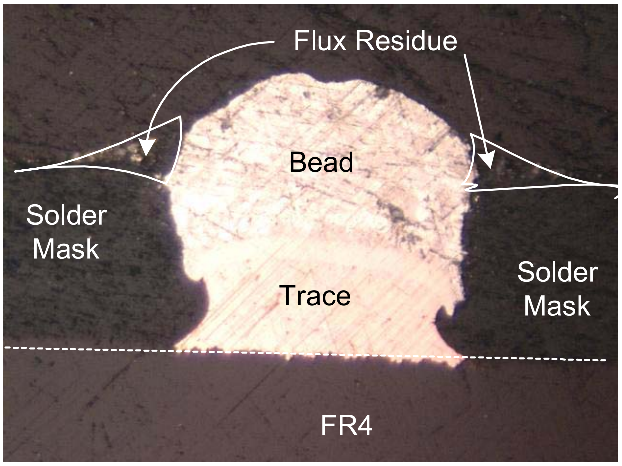

Figure 6: Cross section photo of an unprobed bead fabricated atop an etched trace with CuNiAu plating.

Figure 7 shows a cross section of a bead that has been probed with an 8-ounce probe. The top surface shows the flattening caused by yielding solder.

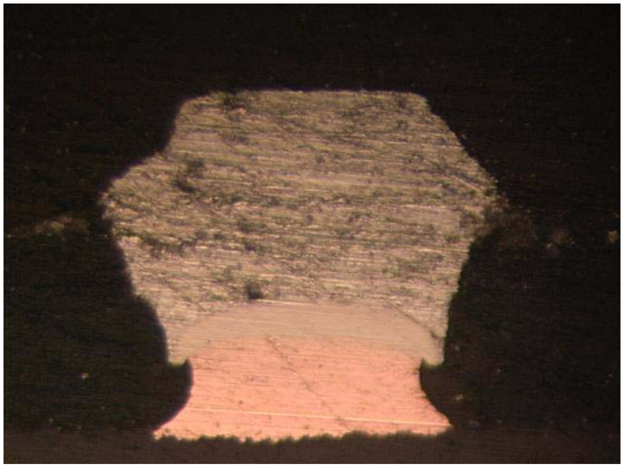

Figure 7: Cross section photo of a probed bead. Note flattened surface.

3 Beads Implemented on a Real Board

At Agilent in Loveland CO, a real board has been designed containing some beads, and several prototype runs have been manufactured. The boards were tested on an In-Circuit Tester with a fixture that mixed conventional probing access with Bead Probe access. The experience has been documented [JaWi05] and is reported here.

The “Talon” board was large 20.5”x16.8” (52x43 cm) and dense, containing 6000 components (on two sides) with 6000 nets. (See Figure 18.) The central section of the PCB contained 3600 nets and was dense enough that full access could not be obtained by laying out conventional probing targets. (The rest of the board did achieve 100% conventional access.) As Bead Probe technology was still in its infancy, the design team took a conservative approach and added beads to only those signals where no conventional access was possible. The philosophy was “if they don’t work, you are back where you were without them”. So, 360 beads were placed in the central region. It was a dense mixed-signal portion of the design containing a lot of discrete analog components. All beads were placed manually using a standard CAD system, observing keepout rules so that fixture target probes would not interfere with nearby components and vice versa.

When the test developer examined the circuit for testability, he decided that he only needed 74 of the beads (approximately 20%) to achieve acceptable test coverage. This may be the first case on record where a design team effortlessly delivered far more test access than a test engineer needed!

However, there were some miss-steps in the process of actually getting beads on boards. There were several prototype runs of Talon. On the first, the CAD system had some quirks that were not noticed by the design team. The result was that the stencil openings for the beads did not propagate into the Gerber artwork. Thus the first run of boards was delivered with nice solder mask openings, but no beads. The designer investigated the idiosyncrasies of the CAD software and made adjustments.

For the second run of Talon boards, the Gerber stencil layout was verified to be correct. However the boards again came back without beads. This time, the stencil was examined and the bead holes were again missing. This time it was because the stencil vendor checked the stencil data, found a lot of diamond-shaped holes they misinterpreted to be erroneous fiducials (the bead paste holes) and silently deleted them.

On the third run of Talon boards, we got back beads in 72 of 74 locations. Those missing were systematically missing from all the boards. As luck would have it, the manufacturing partner (on the other side of the globe) was changed just after this run and we could not find out why those two beads were eliminated.

All these missing beads gave us an opportunity to empirically discover how to “fix” missing beads. We hit upon using a hypodermic syringe to apply a small dollop of paste to a bead location, and then use a pen-sized hot gas soldering tool (e.g., Weller “Pyropen” or Hakko 850B) to reflow the bead. Low air velocity is required to keep the molten solder from blowing away during manual reflow. Subsequent board testing succeeded in spite of these poorly controlled beads.

Figure 8 shows a portion of the central region where beads were placed. Just above one bead and to the right of the other is a surface-mount 0603 size device. The beaded traces are 5 mils wide. Along the bottom are some legs of an integrated circuit. (Beads sit well below the height of these other components and are thus protected from damage from handling.)

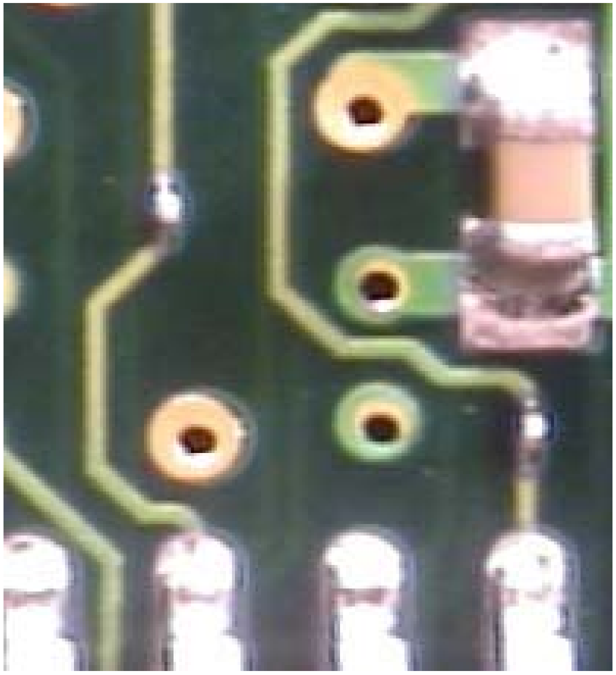

Figure 8: View of two beads on the Talon board.

Figure 9 shows a nicely formed bead from an angle 30 degrees above horizontal. This bead has not been deformed by probing.

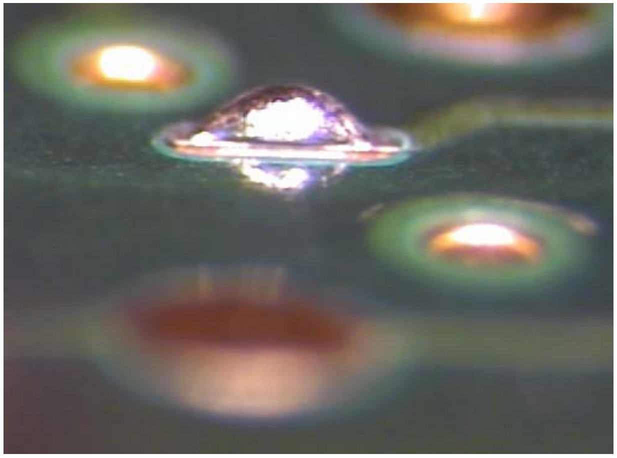

Figure 9: Bead viewed 30 degrees above horizontal.

Figure 10 shows a Talon bead that has been probed. The surface exhibits the classical elliptical flattened area needed to support the spring force, 4 ounces in this case. Note that the solder did not flow quite to the ends of the solder mask opening. Notice that the nearby large pad with a large solder feature on it also did not quite wet to the edge. At this scale, surface tension may deter full wetting and should be accounted for in bead height determination.

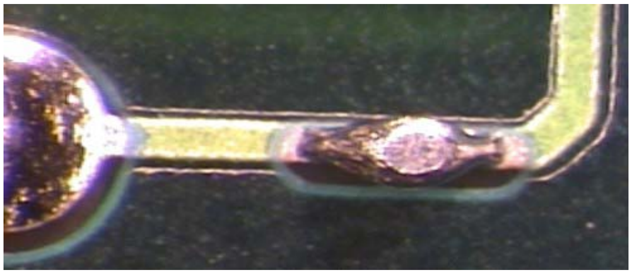

Figure 10: A nicely flattened bead.

We found an interesting example of an overstressed bead, one that had been probed with too much force. (See Figure 11.) We were not in control of the fixture at that time (it was on the other side of the planet) and could not investigate the cause. But we theorize:

1. The fixture probe used had the wrong spring force.
2. The board or fixture platen was not flat at that point.
3. The fixture probe was not seated at the proper depth and thus bottomed out upon fixture activation at test.

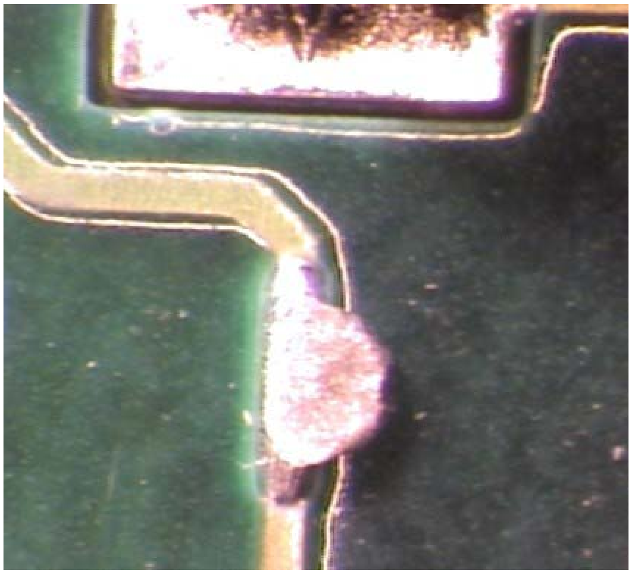

Figure 11: Photo of an overstressed bead. "Anvil-head" deformation due to overstress.

By poking at this bead with a needle point while examining it under magnification it was determined that this deformed bead had an "anvil-head" construction, as depicted in Figure 12. The right side of the head overshadowed the board and thus has the potential to create more capacitance to the ground plane. This could be noticed in the high frequency response of the trace. The deformed solder was also quite fragile, easily moved by the needle point. Thus there is concern that pieces (albeit very small pieces) of anvil-head solder could break off and become loose solder on the board if the bead is crushed by excessive probe force.

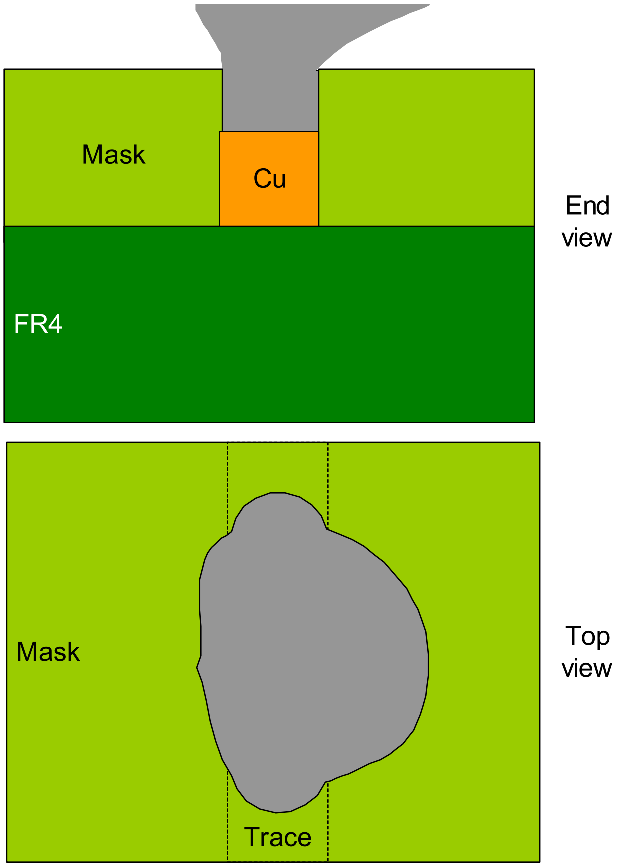

Figure 12: End and top views of an "anvil-head" deformed bead seen in Figure 11.

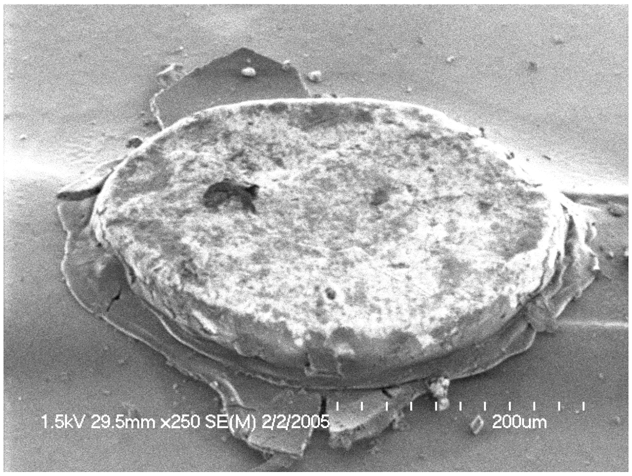

Figure 13: SEM photo (x250) of a catastrophically deformed bead. Note brittle varnish residue.

Figure 13 shows a Scanning Electron Microscope (SEM) photograph of a bead that was deliberately stressed to the crush point. This was done by forcing a fixture target probe onto the bead until full travel (not the usual

67% travel) was achieved, and then a bit more force was then applied to assure catastrophic pressure. Notice in the picture that shards of residue "varnish" protrude out from under the edges of the flattened bead. This is excellent evidence that solder deformation moves contaminants aside for good electrical contact. However, this degree of deformation should be avoided. Compare this bead to an untouched bead such as shown in Figure 14

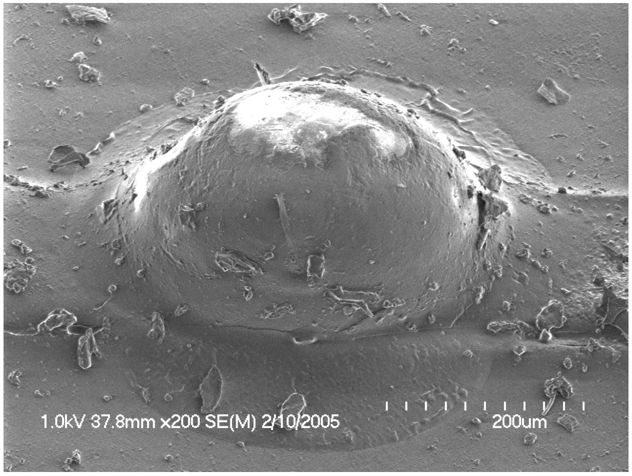

Figure 14: SEM photo (x200) of an untouched bead.

4 Volume Manufacturing Experiments

Agilent contracted with a high-volume board manufacturer to experiment with much higher volumes than generated by the Talon project. At this writing, these experiments are about 60% completed and still in progress. A formal "Design of Experiments" process was conducted to guide this effort. Preliminary results are given here.

Two general types of beads were identified. The first we called "Metal-Defined" beads. These are beads that are constructed on top of printed circuit traces, where the trace width constrains the width of a bead. The second type of bead, called "Solder Mask-Defined", is formed on an area-fill conductor, such as a ground or power plane. (Very wide signal traces such as those that conduct larger currents would also be candidates for solder mask-defined beads.) Note that In-Circuit test fixtures provide access to myriad signal traces, but are also expected to supply raw amperage for powering up a board as well. Many probes are dedicated to this purpose in a typical fixture, with a limit of about 1 ampere per probe. Thus if a board needs 50 amperes at 3.3 volts, you might expect 100 probes (50 at 3.3v and 50 at ground) to be contacting power and ground planes. We expect bead probes to fulfill this need as well, with solder mask-defined construction.

4.1 Bead Reliability – What Is Needed?

The question arises, just how reliable must bead probes be? This can be related to contact reliability probability – that is, what is the probability of getting good contact on a bead probe? If the probability is not high enough, then when a large fixture is actuated, there will be a chance that one of the thousands of beads fails to make decent contact.

For these experiments we defined "decent" contact as being < 1 ohm, and this includes two resistances: 1) the actual contact impedance and 2) the internal impedances inside the probe receptical/probe socket/probe shaft assembly. In fact, most of these summed impedances reported so far [Park04] have been two orders of magnitude under 1 ohm, but with a distribution which is Poisson-like (see Figure 15) bounded by zero ohms on the left, but not on the right, as it is possible for beads to have marginal or open contacts, as is true with any other probing technology. Our experiments defined "marginal" contact to be between 1 and 500 ohms, and "open" to be >500 ohms. Our experiments included some standard probes as well as the bead probes. We observed a trend that well-formed bead probes had lower contact impedances on average, but a wider deviation (Figure 15).

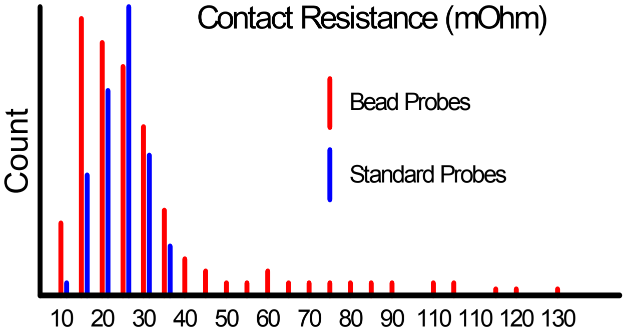

Figure 15: Histogram of contact impedance.

On a manufacturing line there is a desire for fixture contact problems to be very low on the pareto chart of failures experienced during testing. If you had a fixture with 5000 contacts being made, then a contact reliability of 0.9999 for each would translate into about a 61% chance of successful actuation, or less than 2 in 3. This would likely be considered unacceptable. Thus we need better than "4-nines" reliability. At 5-nines (0.99999) we get successful actuations to 95%, or about 19 out of 20 will be good. Expressed differently, we would like 10 ppm (or less) contact failure rate. This would be very competitive with what we achieve today with standard probing. The results reported in [Park04] did not have a large enough sample size to measure contact reliability. The volume experiments being conducted now have sufficient scale.

4.2 Metal-Defined Bead Experiments

To this point, this paper has considered metal-defined bead structures. There are a number of practical issues that have to be considered when you want to create such beads in large numbers with very good reliability.

- Trace widths where beads are desired.
- Expected solder mask registration error.
- Minimum trace spacing.
- Aspect ratio, bead width versus height.
- Contact probe spring force and wiping action.

The first three factors govern the expectation for opens and trace-to-trace shorts. When trace widths are narrow, then solder mask registration error must either be carefully controlled (which is potentially expensive) or you must design solder mask openings larger than the traces to allow for errors. This is because an error may have the effect of skewing the mask opening away from the trace center and that can cause part of the trace to be covered rather than exposed.

The last two factors have to do with bead performance when being contacted. If a very narrow bead is also tall, then the potential for catastrophic bead damage is also heightened. Tall and fragile beads will be more susceptible to damage under larger contact spring force. If the probe also has an engineered wiping action, this can impart lateral forces on fragile beads.

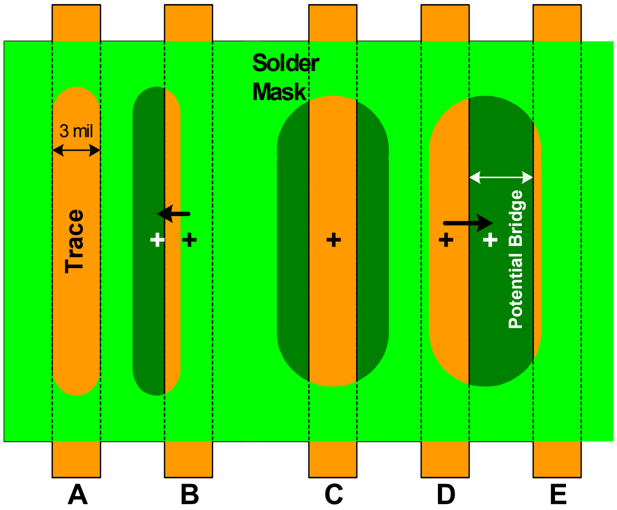

Figure 16: Trace width interactions with solder mask opening widths and registration errors.

In Figure 16 we see several examples of narrow traces (A, B) with matching solder mask openings, and oversized solder mask openings (C, D). Examples A and C show perfect mask registration. However, B shows a matching mask with a leftward error that drastically lessens the available copper for the bead on B to sit upon. This bead may not form properly, it could be much too tall or it may be fragile enough to be knocked off during test. Trace D shows an oversized opening with a rightward error. When registration errors are compensated with oversized solder mask openings, then there is an enhanced probability of trace-to-trace bridging shorts (e.g., D to E) when traces have narrow spacing.

Clearly, missing beads and shorts must be avoided. In our experiments, we built structures with low solder mask registration errors, essentially, those inherent in the build process. We also built identical structures with deliberately inserted solder mask offsets. These demonstrated how opens and shorts would occur as a function of trace and solder mask widths.

Our metal-defined traces were laid out in pairs with varying line and space widths. Some were as small as 3x4 mils and others were as generous as 6x10 mils. Each pair was laid out in a serpentine pattern (see Figure 17) so that a total of 24 beads would be stenciled in 0, 45, 90 and 135 degree rotational offsets with respect to the direction of paste application. In all these cases we let the metal width define the bead width, where solder mask offset errors did not interfere. (All exposed copper had an immersion-silver surface treatment.) Each pair had four standard probe targets on their ends. This allowed us to measure the overall impedance from end-to-end of a trace pair and to check for shorts between trace pairs. If end-to-end impedance of either member of a trace pair showed an open, then we knew our experimental data for that trace should be discarded since there was some other factor at work. If it showed a reasonable value, then we took 4-wire ohms measurements, where the left endpoint injected current into a trace which flowed out of a bead contact under test. The flat-faced probe on the bead had a sense wire on it, as did the right endpoint contact. This gave us the contact-plus-probe assembly resistance, and eliminated the trace contribution.

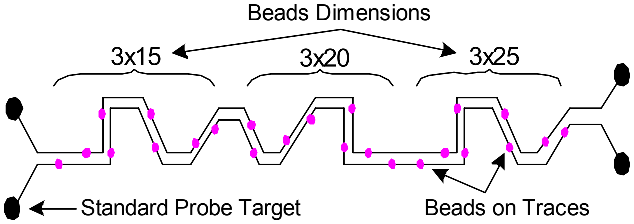

Figure 17: Typical metal-defined trace pair layout.

An In-Circuit test fixture was built to probe all these structures and allow us to measure the contact impedance of each bead. (All beads were Pb-free.) This data was examined in later off-line analysis.

For the first few boards fabricated we also performed visual evaluations of the beads under an angled microscope. Missing beads were noted, and those that “looked bad”. Typically, we observed two general types of beads. The “good” beads had nicely wetted coverage of the copper trace and thus had a “classic” hemi-ellipsoidal shape. These beads were mechanically strong and quite resistant to being knocked off their traces by lateral forces. Poorly shaped beads were most often spherical in shape and did not wet the full length of the exposed copper. They were truly spheres, not hemi-spheres. Thus they had minimal contact area with their trace and were taller and wider than expected. These beads were mechanically fragile and easy to knock off their traces.

Poorly shaped beads were more common on very narrow traces, especially when solder mask errors further narrowed the available wetting area. In effect, the wetting force "lost out" to surface tension force, creating spherical beads.

We also experimented with varying bead lengths, with three lengths chosen (15, 20 and 25 mils). The curious result was that 15 mil beads were more likely to form badly. We are currently testing a hypothesis that again the wetting force loses out to surface tension and that this can be overcome by a change to the paste stencil openings. At this writing, we haven't completed this analysis.

The fixture was populated homogeneously with one of five different flat-faced probe types intended for bead contact. This gave us five distinct data sets, where virgin boards were tested with each probe type. Further, some of the beads were contacted only once, and some 2,3 or 4 times, simulating a re-test scenario. Since the probe types had different spring forces, a given bead may have been overstressed, understressed or properly contacted per the content of Table 2. This allowed us to examine the effects of too much/little spring force.

Contact resistance measurements were made via 4-wire ohms measurements on the In-Circuit tester, for all the beads and probe type combinations. This amounted to several hundred thousand data points, which were then analyzed for trends. This confirmed that badly formed beads have contact problems or are even missing from the board. When we discarded data for beads that were found to have elevated probabilities of poor formation (too narrow, too short) we started seeing very encouraging results that suggest we have already achieved 4-nines reliability. However, we must re-execute the experiments with a new board design that refines our designs based on what this initial pass has taught us. This second pass will have much larger volumes of data that will allow us to measure contact success probabilities.

4.3 Solder Mask-Defined Bead Experiments

Solder mask-defined beads have dimensions dictated by the size of the solder mask opening that exposes copper for wetting during reflow. As long as a solder mask opening is farther way from a copper boundary than the potential solder mask registration error, we should always have the same exposed copper area for each bead.

On our same experimental board, we laid down an area-fill sector, simulating a power/ground plane. On this area we then laid down beads of varying width and lengths and the same rotational offsets, along with some standard probe targets to support 4-wire ohms measurements. These beads were also probed with the same five probe types as used in the metal-defined experiments. We did not expect bead variability due to solder mask registration problems, but were interested in whether width, length, rotation or other factors were at work. For example, a planar copper area will heat differently during reflow. Does this matter?

Measurement data again confirmed the width/length phenomena previously observed also leads to poorly formed beads. So wetting action versus surface tension is indeed a factor in this category of beads as well. Our next design will refine this further.

4.4 One Surprise

One result did startle us. In our first learning experiments for either type of bead we found that there was a notable difference in contact performance for beads that had been reflowed only once versus those that had been reflowed twice. (The second reflow occurs on the side of the board that is processed first, as the pasting and reflow of the other side will necessarily reflow the first side a second time.) We found that twice-reflowed beads had about 5 to 10 times less contact reliability, tantamount to loosing one of our "nines". This has prompted us to do some additional experiments which are underway at this writing to better understand this phenomenon.

4.5 Signal Integrity Experiments

Signal integrity experiments were reported in [Park04] and it was found that Bead Probes have neglible impact on circuit performance. More signal integrity measurements were conducted in this new experimental board. The goal was to build nearly perfect 50 ohm traces with landing patterns at their ends that form ideal connection points for integrity measurements. These traces had solder mask openings for multiple beads on each. The actual number could be decided during the stencil operation.

Integrity measurements again showed negligible effects on signals up to 20 GHz, even with 15 beads evenly distributed across a trace length. The before/after measurements essentially could not separate the bead effects from the noise in the measurements.

5 Conclusion

After another year of experimentation, bead probe technology is still showing good promise. We have conducted testing using bead probes on a (low volume) board now in general production, after several prototype runs demonstrated what we needed to do to get beads on our boards. One key learning there is that because bead probe technology is new, you have to work closely with your board vendor to assure they actually get onto your boards.

We also began volume experiments on a board specifically designed to demonstrate bead probe technology in the face of many variables. These variables include trace widths, trace spacing, bead width and length, mask registration errors, rotational orientation, probing spring force, reflow order, etc. These experiments are still under way. At this time, we believe we will be able to achieve "five-nines" contact reliability.

6 Acknowledgements

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7 References

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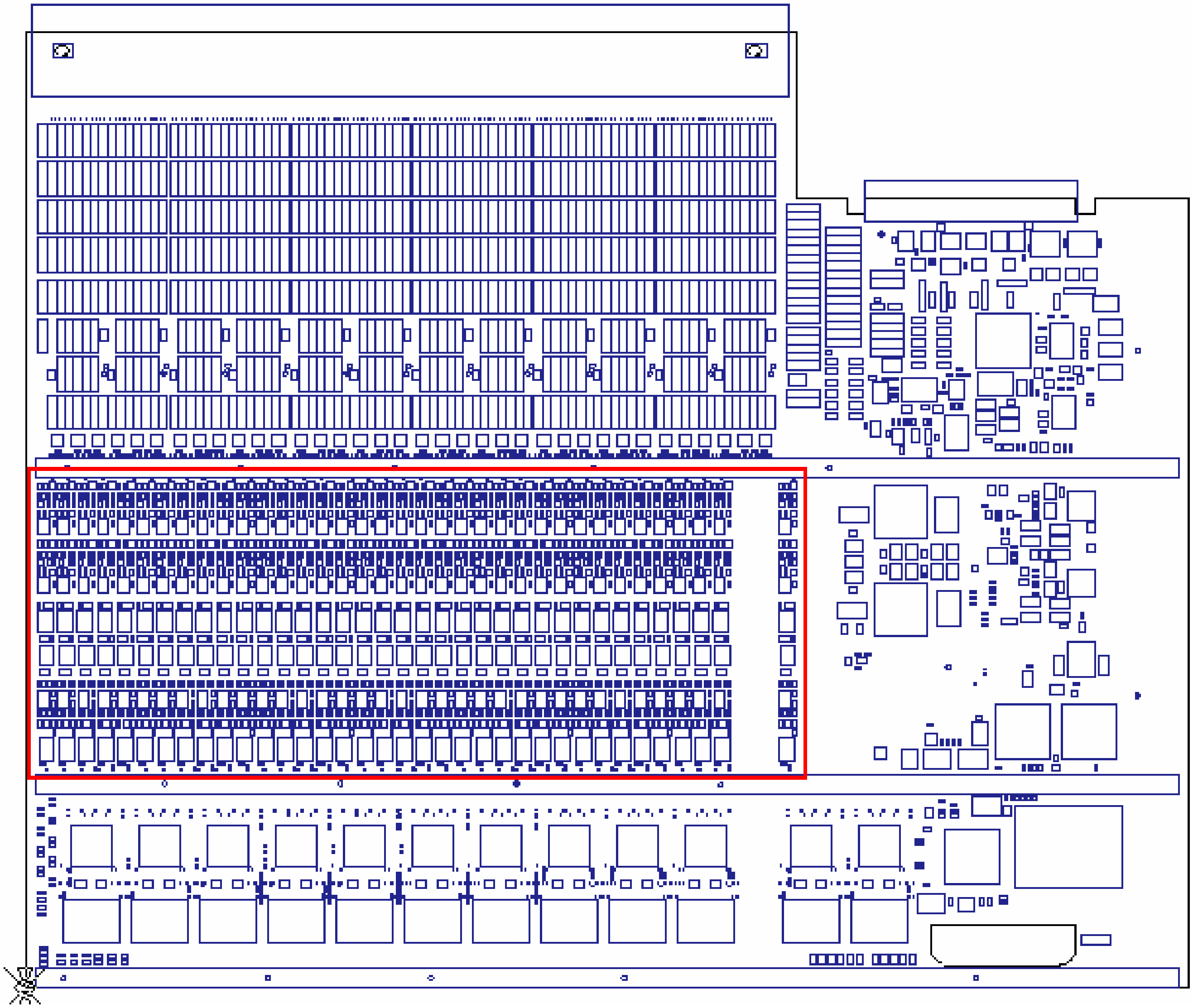

Figure 18: Drawing of the Talon board. The red line surrounds the area where beads were placed.