ADVANCEMENT OF SOLDER PASTE INSPECTION (SPI) TOOLS TO SUPPORT INDUSTRY 4.0 & PACKAGE SCALING

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ABSTRACT

During the past decade, consumer electronics and personal digital devices in particular have shrunk in size but have added significant computing power and capabilities. To enable this digital revolution, the SMT industry has driven towards thinner BGA packages with finer ball pitch and smaller solder ball sizes.

Thinner and finer pitch packages are increasingly prone to warpage with less SMT process yield margin which require intricate stencil design with varying solder paste volume deposits. Increased functionality has driven footprints to be asymmetrical with SMD (solder masked defined) pads which are typically smaller with circular and oval layouts. This has fueled a need for highly accurate and smaller solder paste deposits for increased SMT yield margin and solder joint reliability. Additionally, with the introduction of Industry 4.0 and Smart Factory solutions, it is imperative that data collection must be accurate to influence the appropriate forward and backward feedback information for monitoring, tuning, and automatic adjustments. There is concern that the current industry wide inline solder paste inspection (SPI) tools are operating as gross inspection tools instead of capable metrologies.

This paper evaluates the current state of inline SPI tools from multiple vendors for solder paste measurement accuracy and capability. A measurement capability analysis (MCA) was carried out against a golden metrology tool across a range of volume deposits. Results from the study will highlight the accuracy bias deviations & repeatability of current SPI tools against low volumes deposits and showcase the current gap in the SMT industry.

Key words: Solder paste Inspection, Measurement Capability, Accuracy, Inline SPI.

INTRODUCTION

The SMT Industry and Intel's roadmap are driving to thinner and smaller packages, with finer pitch and smaller ball sizes as shown in Figure 1. This also translates to significantly smaller volume solder paste deposits largely below 250 cubic mils (highlighted in red) as shown in Table 1. Table 1 lists calculated theoretical volumes for small pad sizes. As BGA solder ball pitch decreases, the contribution to the solder joint from solder paste increases (as a function of solder joint integrity). At 0.4mm pitch, printed solder paste contributes ~28% of the total solder joint volume post reflow, approaching 30% at 0.3mm pitch as shown in Figure 2. Data shown in figure 2 are obtained from theoretical calculations. Controlling and accurately measuring solder paste volume is becoming more and more critical as pitch is reduced further. Also, thinner packages prone to warpage need highly accurate solder paste volume deposits to increase yield margins.

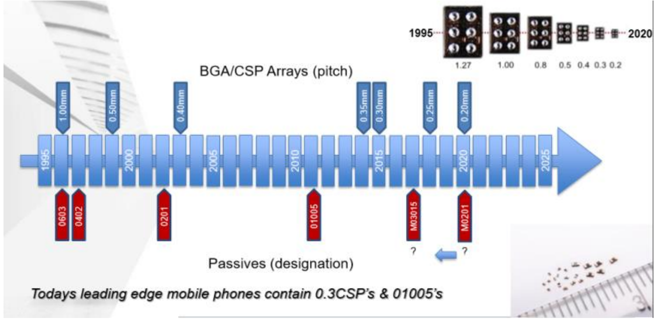

Figure 1. Industry Package form factor roadmap
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Table 1. Solder paste volumes for fine pitch packages

Pitch mm	Spot/Pad Size um (mils)	Volume mil3			
		2 mil (50 um) Stencil/height	3 mil (75 um) Stencil/height	4 mil (100um) Stencil/height	5 mil (125 um) Stencil/height
0.5	300 (11.8)	218	327	436	545
	275 (10.8)	184	276	368	460
0.4	250 (9.8)	150	225	300	450
0.35	200 (7.8)	96	144	192	288
0.3	188 (7.5)	89	133.2	177.6	222
0.25	150 (5.9)	55	82	109	137

Typical SMT Industry upper and lower thresholds for solder paste volume as measured by SPI tools (+/- 50%) are wide and will mask accuracy with false pass. To illustrate this point further consider an SPI measurement scenario shown in figure 3.

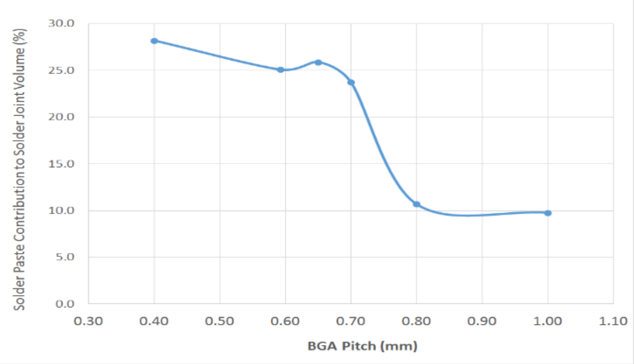

Figure 2. BGA pitch vs. Printed solder Paste Contribution to total Solder Joint Volume post reflow (%)

For a target solder paste volume of 50 cubic mils, the SPI lower and upper control limits of +/- 50 % will be 25 cubic mils (LCL) to 75 cubic mils (UCL). Let us consider SPI accuracy of +/- 20%. For an actual deposit of 30 cubic mils and factoring the accuracy bias error, the measured value of deposit by SPI can be anywhere between 24 to 36 cubic mils. This is shown by 2 arrows from the actual value. If SPI reads 24 cubic mils it will be below LCL and report it as insufficient. This will lead to a a false call and will lead to print downtime and prompt for unenecessary change in printer setting.

Currently inline SPI tools in Industry are marketed as an inspection tool instead of a metrology grade tool. Frequently gage R&R studies using NIST or equivalent calibrated standards are marketed based on their repeatability and reproducibility while accuracy bias is not reported. Smart Factory (Industry 4.0) initiative will drive a need for higher inline SPI accuracy once fully deployed across SMT. This again drives a critical need for accurate inline SPI measurement especially for low solder paste volume deposits.

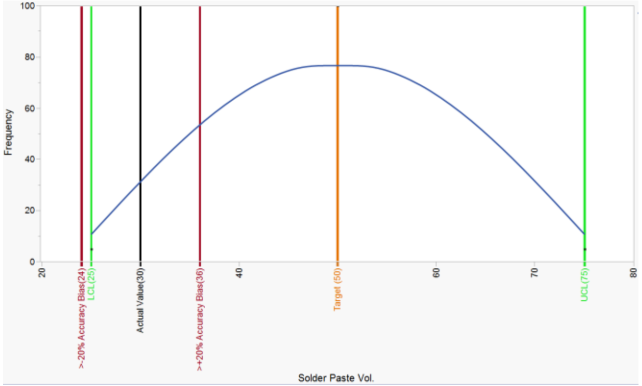

Figure 3. Solder paste measurement scenario for low volume deposit considering accuracy bias of SPI

In our literature survey as well we found that very few reports exist on the topic. Shea et al. [1] reported significant differences in SPI accuracy. According to their study SPI machines always returned values lower than the weight test results. A few other reports and whitepapers [2,3 and 4] from SPI vendors Vi Technology, Cyber Optics, and Marantz electronics emphasize the need for SPI accuracy. Chandru et al. [6] also reported on SPI accuracy and suggested a better offline scanning confocal microscope for more accuracy below 200 cubic mils.

Table 2. Inline SPI tool Vendors and tool camera resolution

SPI Vendor Code name	Tool Camera resolution (microns)	Comments
A	10	Existing older in house tool
B	15	Top of the line tool
C	9	Top of the line tool
D	15	Top of the line tool
E	7	Top of the line tool
A+	5	More updated model from vendor A

With the abovementioned drivers in mind, we set out to gauge industry wide current state of inline SPI tools vis a vis solder paste measurement accuracy of low volume deposits. We tested inline SPI tools from multiple vendors (A through E) as shown in Table 2. For vendor A, 2 tools were evaluated : In-house version tool A and an improved version of tool labeled A+. Total combined market share of the vendors in Table 2 equates to >80% of the North American SPI tools market [5].

METHODOLOGY

Test Vehicle Preparation and Characterization

In order to compare SPI measurement accuracy from different SPI vendors, we created a Golden Reference board (GB). GB was first thoroughly characterized in house using a Golden Reference tool (GT). The GB design is shown in Fig. 4. It is a 10 layer 32 mil thick PCB and consists of BGA, passive and QFP pad structures. Pad structures for all 3 components are a mix of solder mask defined (SMD) and non solder mask defined pads (NSMD). BGA arrays are designed for a 3 mil thick stencil print from AR 0.75 to AR 0.33 and air gap of 4 mils and 5 mils.

To begin with, bare GB was characterized in GT. Next, using a DEK Galaxy printer we printed the GB using 3 mil stainless steel laser cut nanocoated stencil. SAC305 Type 5 solder paste was used to print on GB. Solder paste deposits were dried by heating at 150 degree C for 20 mins. This was done to drive of volatiles and solidify the shape of deposit for multiple measurement use. Post print & drying, SPI was performed using in-house inline SPI tool from vendor A and the GT. Locations are selected from BGA, Passive & QFP pad structures. Pad structure with and without traces were also included (where available) in comparison. Solder paste volume on the PCB ranged from 0 to 900 cu. mils.

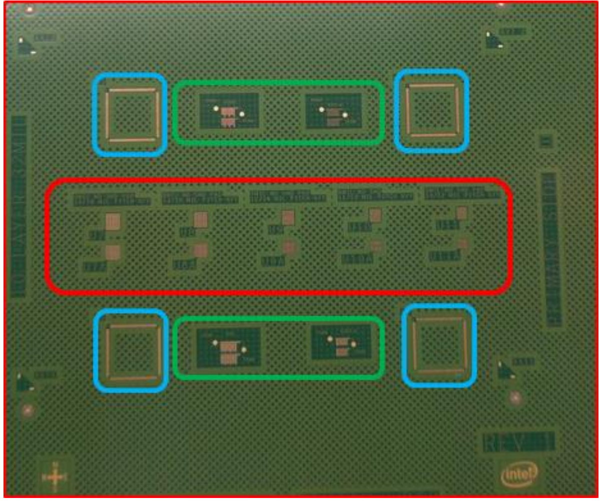

Figure 4. Design Image of Golden Reference Board (Red - BGA Pads, Blue - QFP pads & Green - Passives)

This GB was then sent to selected inline SPI vendors (A through E) for SPI measurement. After the GB was returned, it was re measured in GT to verify the integrity of the solder paste deposits.

MEASUREMENT FUNDAMENTALS

Accurately measuring solder paste deposits' height and volume depends on several factors such as the imaging sensor's resolution, PCB surface undulations, height threshold settings, the PCB's optical characteristics, and the post processing algorithm that computes height and volume. A recent paper [6] describes in detail all of these in addition to proposing a better alternative procedure for measuring solder paste volume.

SPI Basics

Measuring solder paste deposit accurately is not an easy task. First off, the PCB surface is not smooth. It can have local warpage, undulations on surface, etc. Secondly, the solder paste deposit location on the metal pad is a mix of 3 intersecting surfaces: Metal pad/Solder Mask/FR4 PCB material. This complicates identifying and setting up a reference plane for measurement. Thirdly, the solder paste deposit itself is not a perfectly defined cylinder or cube shape. SPI tools use white light and/or laser light to measure deposits. A phase shift Moire Interferometry technique is widely used. White light from projectors is passed through gratings to form interference fringes. It is shone upon the uneven surface of the solder paste deposit and the image is captured at known angles. The shift in the projected interference image is measured using a CCD camera and basic triangulation mathematical techniques are used to calculate the height of the solder paste deposit. Pad area of the solder paste deposit is broken down into pixels and the height of each pixel is determined. The size of each pixel depends on the camera resolution being used. Individual pixel measurement is statistically evaluated to obtain the height of the deposit on a particular pad [2]. To overcome shadow problems, certain vendors use dual projection or more for uniform illumination of the deposit. Besides Moire Interferometry, Laser Triangulation is also used by certain vendors to measure z height of the PCB pad / solder paste deposit.

The exact height of the metal pad with respect to a reference plane is difficult to determine. Most SPI vendors end up setting thresholds (industry spec is around 40 microns) below which measurement is ignored. For more accurate and slower measurement route, bare PCB is run through the SPI tool first before printing. PCB warpage, surface morphology and pad height is captured and taught. Next, a pasted PCB is run and bare PCB pad height is subtracted from the solder paste height calculation.

GT Measurement Basics

GT is a non contact profilometer with an X-Y motion system. It uses a chromatic white light sensor. Working principle in brief is as follows. Polychromatic White light composed of several wavelengths is focused on the object surface. It is well known that different wavelengths have different focal lengths. For any point on the sample surface, one reflected wavelength component of the white light will have the maximum intensity relative to all other wavelengths. The spectrum of reflected light is analyzed using a spectrometer. If a particular wavelength is exactly focused on the target, the spectrum has a maximum at this wavelength and shows a peak. To each wavelength, a specific distance to the target is assigned by calibration. Therefore, by knowing the wavelength with highest intensity, it is possible to accurately map the height profile point by point over the entire sample surface.

Key differences are to be noted between inline SPI tools and GT. GT is a lab scale metrology grade tool with focus on accuracy and resolution vs. throughput. Its height and depth resolution is ~160 nm and spatial resolution could be down to 1 micron. GT runs much slower than SPI tools. Inline SPI tools are automated tools with focus on speed and throughput. These tools are gross inspection tools. GT and SPI use completely different optics and technologies to perform the measurements.

RESULTS & DISCUSSION

GB was measured on GT and then sent to various SPI vendors (A through E) for measurement. All the vendors were provided the same board and stencil gerber data for recipe creation and measurement. Accuracy bias in volume % measured was calculated and compared using the following formula: Accuracy Bias % = $(\text{Vol}_{GT} - \text{Vol}_{X}) * 100 / \text{Vol}_{GT}$, X here denotes different SPI vendors. All the SPI tools evaluated in this study are based on shadow free Moire technology. Camera resolution is different for each vendor and noted in Table 2. Besides camera resolution, there are other hardware and compute algorithm differences among SPI vendors A through E. Select pads from BGA, QFP, and passive components were used for accuracy bias measurement. Solder paste volume of these components is in the range of 0 to 900 cubic mils. Solder paste volume ranges were divided into 3 phases : Phase 1 : 0 to 100 cu.mils, Phase 2 : 101 to 250 cu.mils and Phase 3 : 251 to 900 cu mils. Allowable accuracy bias variation criteria was kept at +/- 20 %. Accuracy bias for phase 1 volume range is plotted in figure 5 a and b. We can clearly observe that for very small paste volume deposits between 0 to 50 cubic mils for passive and BGA components (figure 5a), all the vendors except A+ show a higher bias variation than 20%. Tool A+ is a newer version with a much higher resolution camera and software upgrades from vendor A. Also, the measurement is performed without any threshold setting on the A+ tool. Tools A and B perform worse for small volume measurements with a huge accuracy bias %. For the 51 cubic mil to 100 cubic mil solder paste volume range shown in figure 5b, only tools A+ and C meet the criteria. The rest are failing either for a positive or a negative bias percentage.

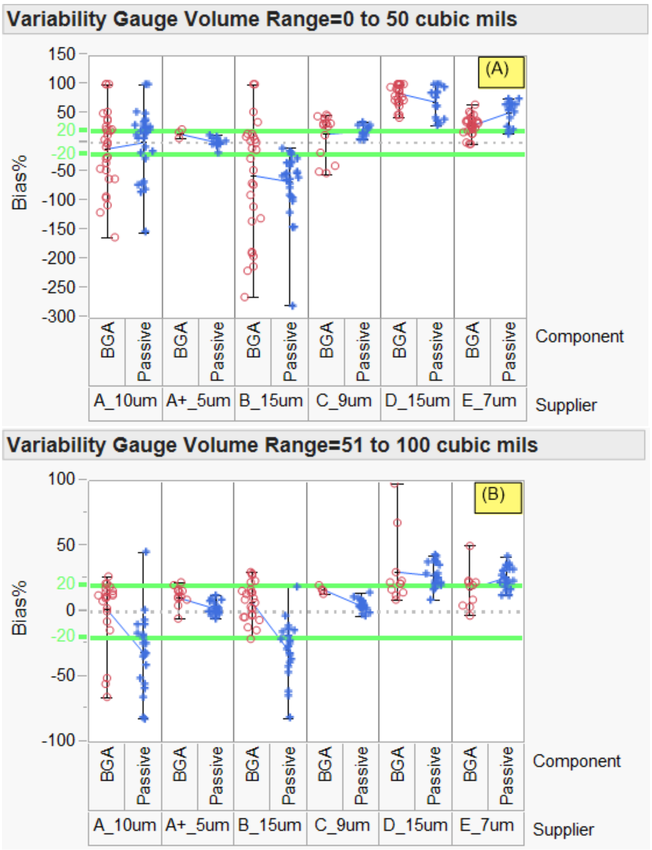

Figure 5A&B. Variability chart for Bias % for phase 1 Volume range

Phase 2 solder paste volume ranges are further broken down in 3 sub parts for analysis as shown in figures 6a, b & c. Part 1 varies from 101 to 150 cubic mils. Only tool A+ meets the criteria as evident from the plot. Part 2 varies from 150 to 200 cubic mils. In this range again only tool A+ is able to fully meet passing criteria. Tools B and C are barely failing criteria for BGA and QFP pads respectively. Part 3 varies from 201 to 250 cubic mils. Tools A, A+ ,C & E meet the passing criteria.

Similarly, Phase 3 solder paste volume range is broken down in two sub parts as shown in figure 7a & b. Part 1 varies from 251 to 499 cubic mils. Most tools are able to meet the passing criteria except for tool D. Tool D is barely failing the upper limit. Part 2 varies from 500 to 900 cubic mils. We observe almost all the tools passing the criteria except tool C which is barely trailing by few percentage points on the upper limit of the passing criteria.

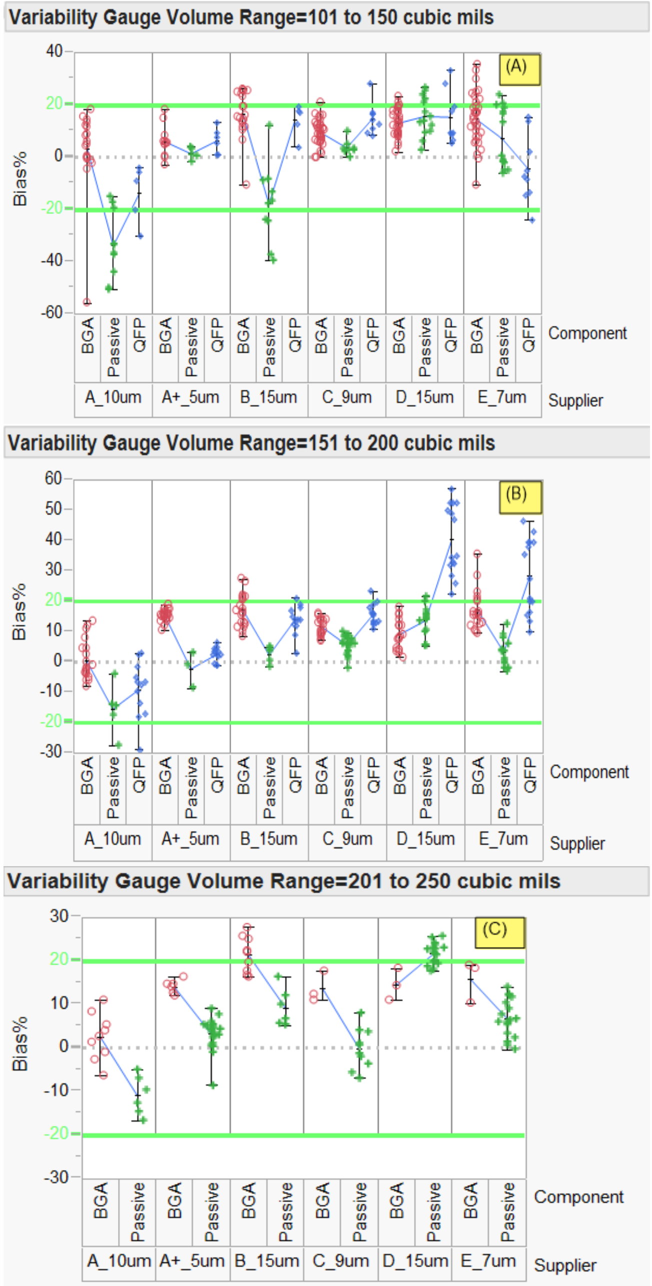

Figure 6A,B&C. Variability chart for Bias % for phase 2 Volume range

As we move from low to higher volume paste deposits, more tools are able to meet the passing criteria. In our industry survey with various SPI vendors, we found that when these tools are calibrated using NIST or equivalent targets for qualification, more often than not minimum volume of structures on the NIST standard is ~ 500 cubic mils or higher. This explains large accuracy bias observed for low volume solder paste deposits below 250 cubic mils. Only tool A+ with the highest resolution camera is able to meet the passing criteria.

Another point to be noted is that the majority of these tools (except A+ and B) employ Z height threshold >10 um to estimate. They ignore the height and volume of the metal pad in the solder paste deposit calculation. For large volume deposits, metal pad volume contribution will be small and may not affect accuracy bias as much. Software algorithms and implementations can vastly vary from vendor to vendor. It is clearly evident that threshold free measurements along with correct hardware is more accurate for low solder paste volume deposits.

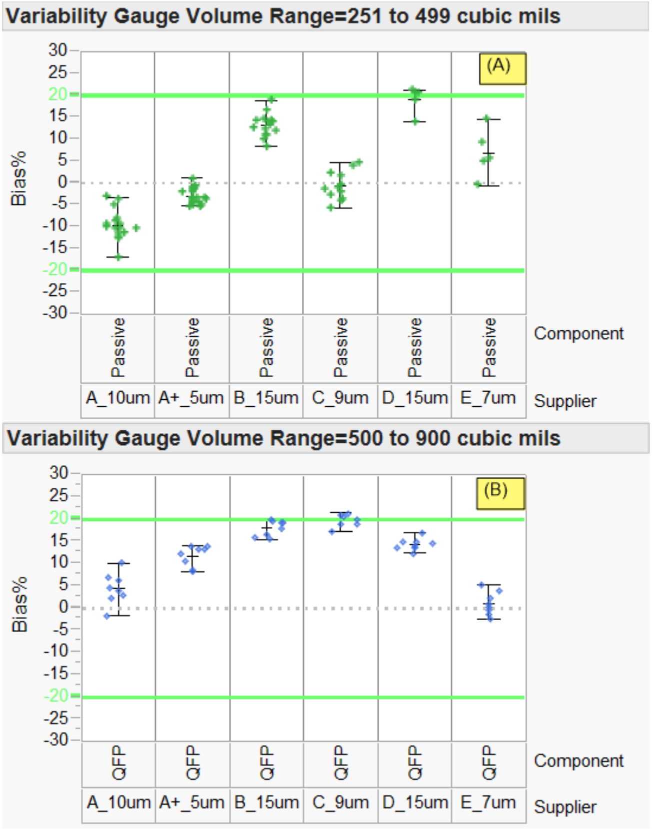

Figure 7A & B. Variability chart for Bias % for phase 3 Volume range

CONCLUSIONS & RECOMMENDATIONS

The results of the study showed increased sensitivities to low solder deposits of less than 250 cubic mils across SPI equipment employing threshold algorithm values >10 um and spatial resolution ≥7 um. Evaluations on a 5 um resolution system (A+ tool) employing 0 um threshold algorithms were found to have acceptable accuracy deviations of less than +/- 20%.

In order to improve inline SPI accuracy for low solder paste volume deposits, SPI vendors must consider calibration of SPI tools with lower volume (below 200 cubic mils) NIST or equivalent standards. For fine pitch applications as well as lines configured for Industry 4.0, accuracy should be a consideration for SPI tool selection.

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