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ABSTRACT

Due to the increased use of Ball Grid Arrays (BGAs) and fine pitch and ultra fine pitch Quad Flat Packages (QFPs), there is a dramatic increase in demand for solder paste inspection after the stencil printing process. The important response variables of the printing process are deposited solder paste volume, area, height and position. To identify and remove defects at the earliest possible process step, a 3-D solder paste inspection system should be used to monitor solder paste deposited on all pads on every board before component placement. An example is a fully automatic laser-based 3-D triangulation solder paste inspection system that is currently used for inspection of 0.635mm (25mil) pitch QFP components of automobile electronics products. As the pitch of QFP components decreases and the use of BGA components increases, the gauge repeatability & reproducibility (R&R) of the inspection system must be reevaluated. This work investigates whether the present system can be used for measuring 0.4 mm and 0.3mm pitch QFPs and BGAs. An experiment was conducted featuring 2,400 pads of 5 different pitch levels of QFPs and BGAs from 0.3mm (12mil) to 0.76mm (30mil). The analyses show that the system is capable of measuring solder deposits higher than 0.025 mm (1 mil) with repeatability of 5% for volume and area measurement, and with repeatability of 5% for average height of the majority of pads and 18% for all pads. In addition, there are requirements in board design necessary to ensure the reference points for measurements can be specified close enough to the pads.

Keywords: measurement, repeatability & reproducibility (R&R), triangulation, solder paste inspection

1. Introduction

As the pitch of components decreases and tighter tolerances are required, more advanced measurement machines must be developed to meet the challenges. The purpose of a measurement machine is to provide data accurately represent real product dimensions.

It should be noted that gauge repeatability & reproducibility in one range might not extend to other ranges since the variance might depend on the mean level of the measurement. For example, if a solder paste inspection system can measure volume of solder paste for 0.635 mm (25 mil) pitch within required repeatability, it does not guarantee the system can measure the volume of solder paste for 0.3 mm (12 mil) pitch within the required repeatability. A fully automatic laser-based 3-D triangulation solder paste inspection system is currently used for inspection of 0.635mm (25mil) pitch QFP components of automobile electronics products. This paper presents an investigation of whether the present system can be used successfully for measuring 0.4 mm and 0.3mm pitch QFPs and BGAs.

2. Gauge Accuracy, Repeatability, and Reproducibility

Measurements typically act as random variables the behavior of which can be summarized by a mean (μ) and variance (σ). It is well known that the measured data includes the variation of the product and the variation of the measurement machine.

$$\mu_{total} = \mu_{product} + \mu_{measurement}$$
$$\sigma^2_{total} = \sigma^2_{product} + \sigma^2_{measurement}$$

where μ_{total} is the observed average of a set of measurements; $\mu_{product}$ is the true mean of the measured product; $\mu_{measurement}$ is the measurement system bias (e.g. gauge accuracy); σ^2_{total} is the overall variance; $\sigma^2_{product}$ is the variance of the measured product; and $\sigma^2_{measurement}$ is the variance caused by the measurement system and measurement procedures.

The gauge repeatability is defined as the measurement variation caused by a measurement system measuring the same dimension many times using the same measurement methodology. The gauge reproducibility is the measurement variation obtained by different operators measuring the same dimension. For fully-automated measurement systems requiring no operators, gauge reproducibility might be ignored though sometimes it may be used to characterize variation associated with different parts of the machine or difference machines. The machine-to machine reproducibility can be evaluated by their degree of correlation. Melendez [5] suggested that the reproducibility component could be evaluated by changing time, board alignment or fixturing or board orientation.

A proper measurement system should be unbiased and have sufficient capability to detect variation in the product, which requires that $\mu_{measurement}$ be close to 0, and that the ratio of $\sigma^2_{measurement}$ to $\sigma^2_{product}$ be small enough. Gauge accuracy is achieved by calibrating the measurement system to a traceable reference standard.

The objective of a gauge repeatability & reproducibility analysis is to identify and quantify the sources of the measurement variability. Generally, the sources of the measurement variation include 1) instrument variation, 2) measurement process variation, 3) operator related variation, 4) variation among test samples, 5) environmental fluctuations [3].

3. Absolute Measurement & Relative Measurement

The measurement system performance parameters (accuracy, repeatability & reproducibility) can be evaluated in two ways. One is called "absolute measurement" in which the measurement system is calibrated to a traceable reference standard such as one set by the National Institute of Standards and Technology (NIST). The resulting data is verified against the absolute values. This process is normally done by the manufacturers of measurement systems. All performance parameters can be obtained by this method.

The method commonly used in production is "relative measurement," which assume the average of a number of performed measurements as the nominal value. In this way, gauge repeatability & reproducibility can be evaluated, but not accuracy since the true values are not known (the average of the measured data may be biased).

4. Analysis Method

One classical and simple way to analyze the gauge capability is to use X-bar and R charts [1, 2, 3]. Precision-to-tolerance (P/T) ratio is commonly used as an index of gauge capability. The P/T ratio is defined as the ratio of $6\sigma_{measurement}$ to the total tolerance range (the difference between the upper and lower limits of the specified tolerance). Generally, a value of P/T of 0.1 or less means it is a proper gauge. However, Montgomery and Runger [1] point out that there are dangers in relying too much on the P/T ratio as they may be made arbitrarily small by increasing the width of the specification range. They recommend using the ratio of $\sigma_{measurement}$ to $\sigma_{product}$ or $\sigma_{measurement}$ to σ_{total} as a gauge capability index. This method presupposes a reasonable statistics background to design and analyze the experiments.

In this paper, the ratio of $\sigma_{measurement}$ to the mean of the measured value is used as a gauge repeatability index. Since the deviation of a set of measurements normally depends on the mean level of the measured value, the index is reasonable and satisfies engineering requirements. Using this index, analysis of the measurement repeatability for an automated measurement system is simple and easy.

5. Triangulation Principle

Laser triangulation is considered the most effective method for high speed and high resolution 3-D SMT inspection [7]. Double triangulation techniques can reduce the shadow effects present in single triangulation. A double triangulation system is shown in Figure 1. The laser beam is swept across solder deposits and height reference points on a printed circuit board (PCB). The light scattered from the solder deposits is captured by two Position Sensitive Devices (PSD). As the deposit height changes by ΔH, the light reflected on the PSDs moves ΔD as indicated. The two images are analyzed and the height profile of the deposit is calculated. The measurement system has resolution settings of 18 μm, 25 μm, and 36 μm, which can be selected depending on the smallest lead pitch in the PCB.

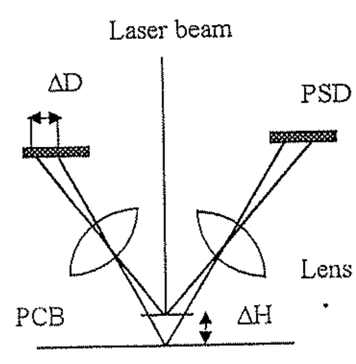

Figure 1. Laser Triangulation

Warpage of PCBs may have significant influence on the measurement accuracy and capability since the warpage will result in uncertainty of the reference height of the PCB. The volume and height of the solder deposits become smaller as the lead pitch is decreased. The small deposits may be more sensitive to the warpage. Though most warpage of PCBs can be eliminated by a proper clamping mechanism, minimizing the influence of the remaining warpage is necessary. In this measurement system, up to 10 local reference heights close to the solder paste deposit to be measured can be selected. From these local reference heights, the "virtual" exact reference height at the solder paste deposit is calculated.

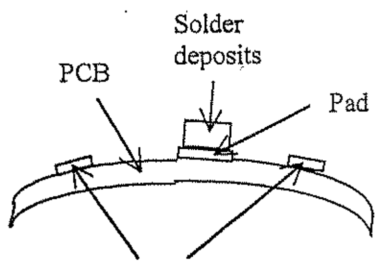

Figure 2. Board warpage with local reference heights and solder pad

6. Gauge Repeatability Analysis of a 3-D Solder Paste Inspection System

A fully automatic laser-based 3-D triangulation solder paste inspection system is currently used for inspection of 0.635mm (25mil) pitch QFP components of automobile electronics products. As the pitch of QFP components decreases and the use of BGA components increases, the gauge repeatability of the inspection system must be reevaluated since the repeatability may relate to the mean level of measured value.

An experiment was conducted to investigate whether the system can be used successfully for measuring 0.4 mm and 0.3mm pitch QFPs and BGAs. A test board featuring 0.76 mm (30 mil), 0.6 mm (25 mil), 0.5 mm (20 mil), 0.4 mm (16 mil), and 0.3 mm (12 mil) pitch QFP and BGA was designed. A total of 2,400 pads are on the board. In solder paste inspection, volume, area, and height of the solder paste deposited are considered important measurements. After stencil printing, the volume, area, and average height of solder paste deposited on all pads were measured by the 3-D inspection system 10 times. Therefore, a total of 72,000 data points were obtained.

As mentioned in Section 4, the gauge repeatability is defined as the scatter of standard variation of a set of measurements with respect to its average. The data manipulation for the repeatability test was performed on an excel spreadsheet. The mean and standard deviation of a set of measurements on each pad are calculated. An X-Y chart of mean and standard deviation is then plotted. If all scattered points are below a line with a slope of 0.05, it means its repeatability is less than 5%.

The repeatability chart of solder deposit volume is shown in Figure 3. The results indicate that there are three outliers and the repeatability is larger than 5% when mean volume is small. A microscope was used to check these three deposits and it found that the volumes measured by the inspection system were much lower than they should be and the results were uncertain. After investigating and consulting the manufacturer of the inspection system, it was concluded that these three deposit volumes uncertainty might be due to the improper reference points selected. The reference points of these three pads consist of two parallel lines and the points are far from the pads. Note that the reference points were automatically determined by the inspection system. The improper reference points may result in the algorithm of the measurement system having difficulty in determining the reference plane so that the measurement results were uncertain.

The repeatability charts of solder deposit area and average height are shown in Figure 4 and Figure 5. Figures 3, 4 and 5 show that the repeatability becomes unacceptable when the mean values are very small. After removing all data of the 0.3 mm (12 mil) and 0.4 mm (16 mil) pitch BGAs and the three outliers, the repeatability of volume, area, and average height are shown in Figures 6, 7, and 8. Results indicate that the system is capable of measuring the volume and area down to 0.3mm (12 mil) pitch QFPs and 0.5 mm (20 mil) pitch BGAs within the repeatability of 5%, while the repeatability of height for all deposits is within 18% and for the majority of the pads is within 5%. It was observed that the heights of most 0.4 mm and 0.3 mm pitch BGAs measured by the system were zero. These pads were checked then by a microscope and it found that there were solder deposits though some pads only had several solder particles. It was concluded that the system may consider all solder deposits lower than 0.025 mm (1 mil) as zero. Therefore, the inspection system may be capable of measuring 0.4 mm and 0.3 mm pitch BGAs if more solder deposits was deposited at the pads.

7. Conclusions

In this paper, a method to estimate the repeatability of an automatic measurement system is discussed. A 3-D solder paste inspection system is analyzed and the results show that the system is capable of measuring solder deposits higher than 0.025 mm (1 mil) with repeatability of 5% for volume and area measurement and with repeatability of 5% for average height of the majority of pads and 18% for all pads. In addition, there are requirements in board design necessary to ensure the reference points for measurements can be specified close enough to the pads.

8. Biography

Jianbiao Pan is currently a Ph.D. candidate in the Department of Industrial & Manufacturing Systems Engineering at Lehigh University. His research interest is in electronics manufacturing processes and systems, and quality control. He is a member of IMAPS, IEEE, and SME, and the chair of the SME Lehigh University Student Chapter during 1997 ~ 1998. He was awarded the 1998 Outstanding Student Officer Award from SME Region 3.

Dr. Gregory L. Tonkay is Associate Professor in the Department of Industrial and Manufacturing Systems Engineering at Lehigh University. He is the Director of the Electronics Manufacturing Laboratory and Associate Director of the George E. Kane Manufacturing Technology Laboratory. He has authored or co-authored over 25 technical papers. His areas of interest are manufacturing, automation, electronics manufacturing, and engineering education.

Dr. Robert H. Storer is Professor of Industrial and Systems Engineering, and Co-Director of the Manufacturing Logistics Institute at Lehigh University. He received his B.S. in Industrial and Operations Engineering from the University of Michigan in 1979, and M.S. and Ph.D. degrees in Industrial and Systems Engineering from the Georgia Institute of Technology in 1982 and 1986 respectively. His interests lie in applied statistics and operations research.

Ronald Sallade is currently employed at Cygnus, Inc in the development of medical device manufacture for the Biotechnology industry. Mr. Sallade, formerly employed at the Advanced Manufacturing Technology Division of the Visteon enterprise of Ford Motor Company, has made extensive improvements in manufacturing for the electronics industry in the areas of screen printing and machine vision. Developments in the screen printing arena awarded him Ford's President's Award for Customer Driven Quality as a member of the Worldwide Screen Printing Process Improvement Team. Mr. Sallade graduated Magna Cum Laude from the University of Pennsylvania with a Bachelor of Science in Mechanical Engineering and Applied Mechanics.

Dave Leandri is a Manufacturing Engineer in the Manufacturing, Design & Development Department for Visteon Automotive Systems. He holds a B.S. in Ceramic Engineering and a M.S. in Engineering Science from Penn State University. Currently, he is pursuing a M.S. degree in Technical Management from the Univerity of Pennsylvania/Wharton. For 6 years he worked on hybrid material selection and processing, more recently working on SMT processing. Prior to joining Ford, Dave worked as a Development Engineer at Ferro Corporation.

9. Reference

[1] Douglas C. Montgomery and George C. Runger, "Gauge Capability and Designed Experiments. Part I: Basic methods", Quality Engineering, Vol. 6, No. 1, pp. 115-135, 1993.

[2] Douglas C. Montgomery and George C. Runger, "Gauge Capability and Designed Experiments. Part II: Experimental Design Models and Variance Component Estimation", Quality Engineering, Vol. 6, No. 2, pp. 289-305, 1993.

[3] Syed E. Haider, Faa-Ching Wang, John Capps, and Ron Price, "Metrology Control for an Advanced 200 mm Sub-Micron Wafer Fab", Proceedings of the 17th IEEE/CPMT International Electronics Manufacturing Technology Symposium, Austin, TX, pp. 88-95, 1995.

[4] Russell J. Elias, "Statistical Process Control for Semiconductor Metrology Systems", Semiconductor International, pp. 167-172, October 1996.

[5] Carlos A. Melendez, "Characterizing and Controlling the Process", SMT (Special supplement: Guide to Soldering & Printing), pp. 9-10, January 1999.

[6] Douglas C. Montgomery, Design and Analysis of Experiments, John Wiley & Sons, 4th edition, New York, pp. 472-475, 1997.

[7] D. J. Svetkoff, D. N. Smith, and B. L. Doss, "Automatic Inspection of Component Board Using 3-D and Greyscale Vision", Hybrid Circuits, No. 13, May 1987.

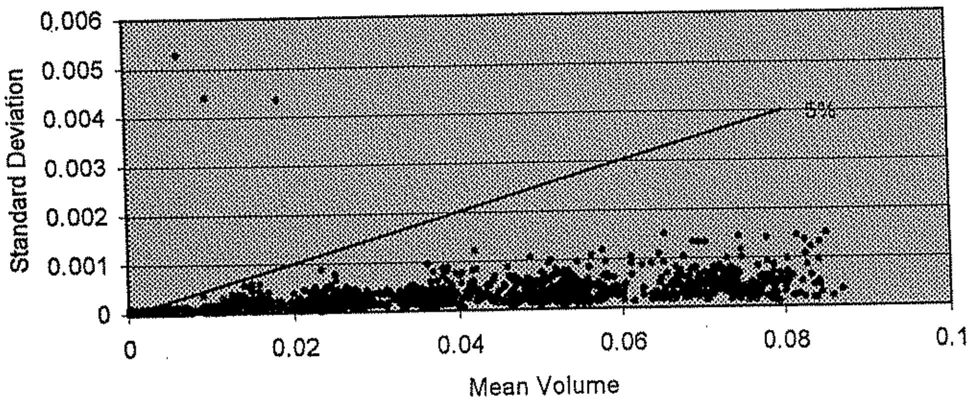

Figure 3. Repeatability of the Solder Deposit Volume

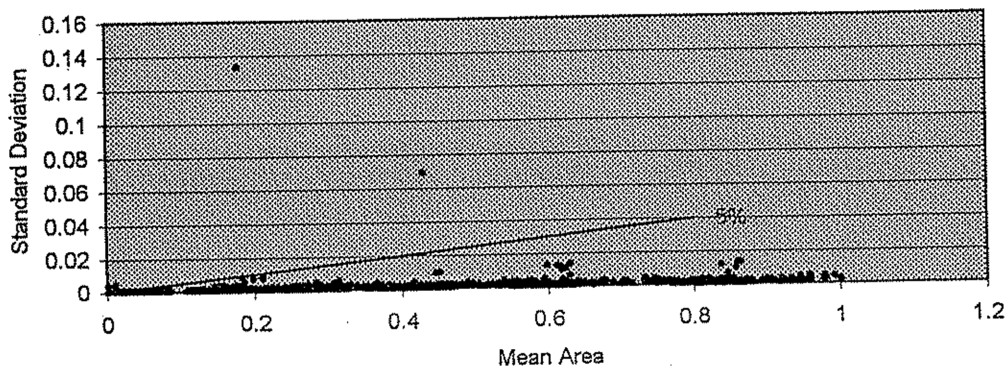

Figure 4. Repeatability of the Solder Deposit Area

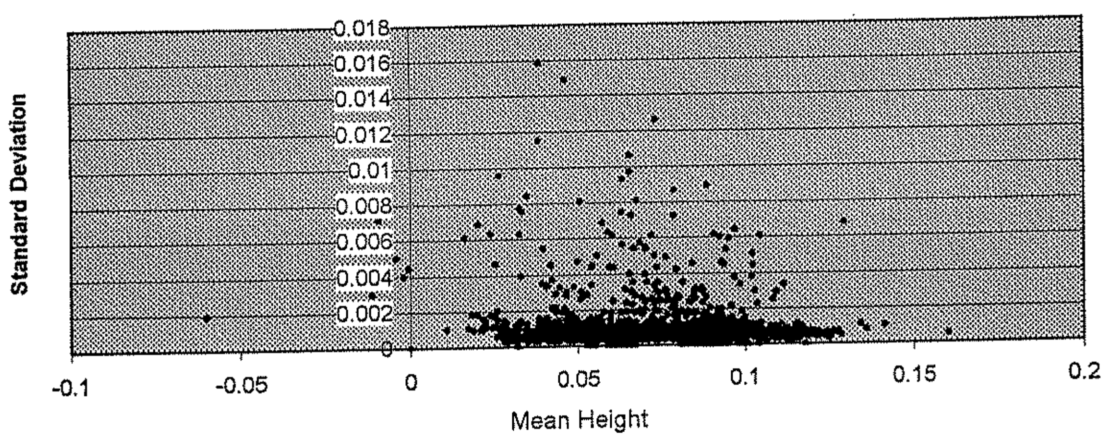

Figure 5. Repeatability of the Solder Deposit Average Height

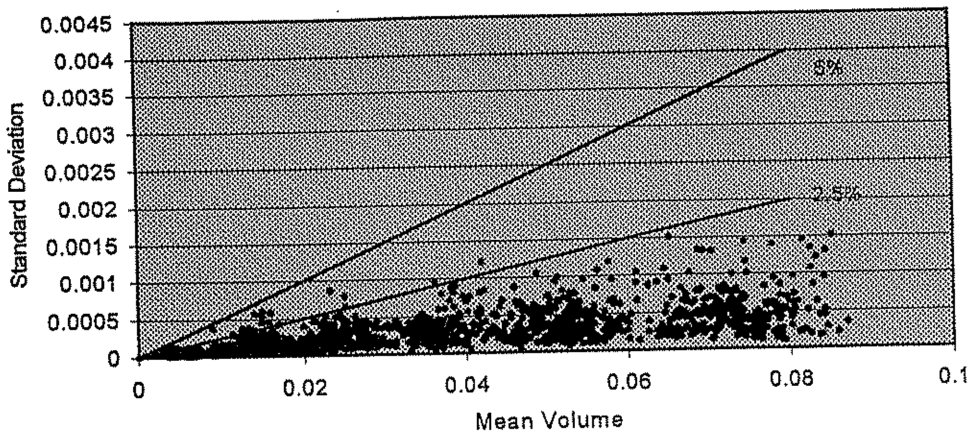

Figure 6. Repeatability of the volume measurements without 3 outliers and BGA 0.3 mm and 0.4 mm pitch

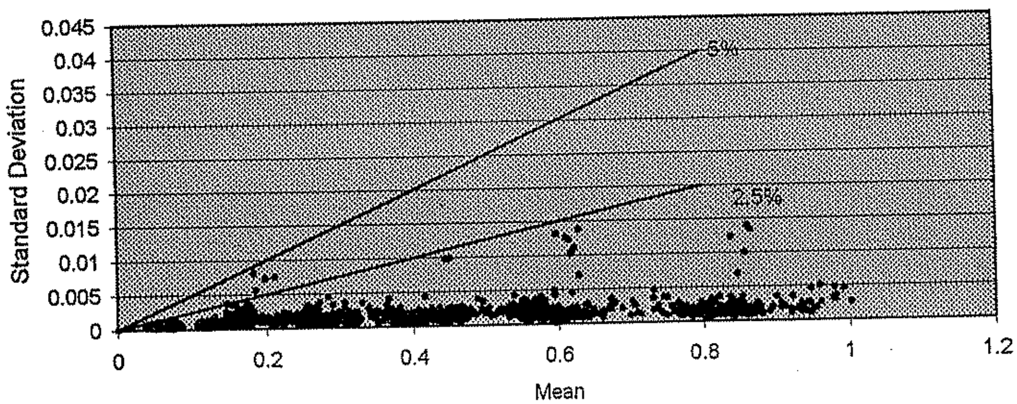

Figure 7. Repeatability of the area measurements without 3 outliers and BGA 0.3 mm and 0.4 mm pitch

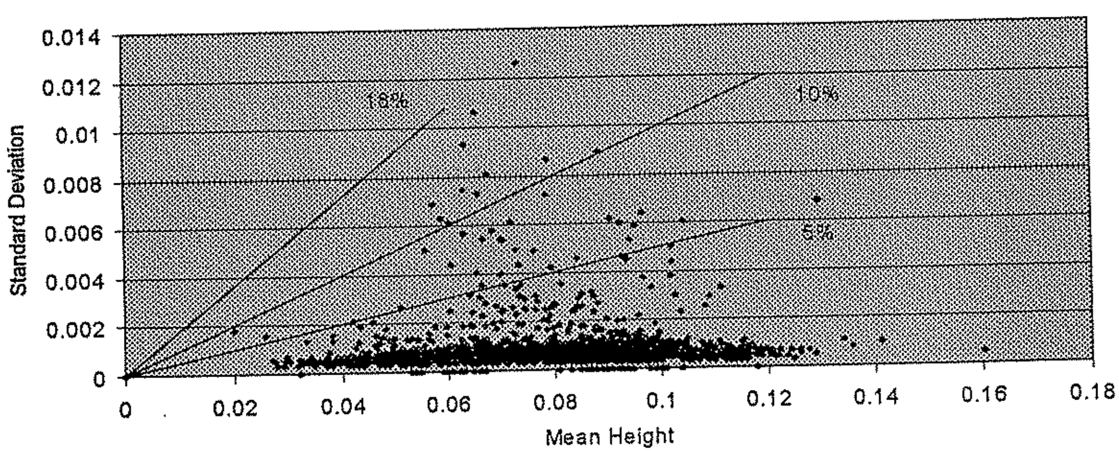

Figure 8. Repeatability of the average height measurements without 3 outliers and BGA 0.3 mm and 0.4 mm pitch