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VARIABILITY IN THICKNESS MEASUREMENTS USING X-RAY FLUORESCENCE TECHNIQUE

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ABSTRACT

Thirty units of tin plated Dual In-line Packages were used to evaluate the measurement system for tin thickness using the X-ray Fluorescence technique. The results showed that the system is sensitive to inspector technique and the total measurement error estimate was about 22 microinches. This system for obtaining tin thickness measurements had been recommended only when the variability of the process is at least 80 microinches. Otherwise, a more sensitive method must be used.

1. INTRODUCTION

In a manufacturing environment, tons of data are gathered for the purposes of process information, process design, process control, and process improvements. The precision and accuracy of these measurements are often neglected and assumed to be of high quality by the users. However, in reality, one cannot be highly confident that the assumption of a good measurement system is always valid.

Measurement system refers not only to the measuring equipment but also to the procedures and inspector techniques involved in obtaining the observation.

The primary problem posed to a manufacturing environment by assuming that one has a good measurement system when in reality its performance is unacceptable is that of arriving at the wrong conclusions about the data gathered. For instance, a true shift in a process may not be detected due to the large measurement error relative to the process variation or an off-spec unit may be accepted due to the failure of the measurement system to discriminate between good and bad readings.

Tin plating is a subprocess in the assembly of integrated circuits in which tin thickness is one of the key output variables. Quality assurance inspectors monitor the thickness of the plated units at a regular basis using the data to monitor the process and to hold or accept lots plated.

Presented in this paper is an illustration of a potential measurement capability (meascap) study done on the tin thickness measurement system using X-ray Fluorescence technique. It is a pilot study for the purpose of obtaining preliminary data regarding the measurement error of this system. Specifically, it aims to answer the questions: 1) How much is the measurement error?, 2) How much variability is attributed to the XRF equipment?, 3) Is this technique of measuring tin thickness sensitive to inspector technique?, 4) Can this measurement system discriminate between good and bad thickness readings?, 5) Is this technique a good measurement system for tin thickness?.

2. BACKGROUND

X-rays are electromagnetic radiation of about 1 to 100 A^0 in wavelength. They are identical in nature to visible light in which periodically variable electric and magnetic fields are perpendicular to each other and to the direction of propagation. In general, x-rays are generated as a result of energy transitions of electrons caused by the bombardment of a material by accelerated, high-speed electrons. When a material is radiated by x-rays with energies greater than the critical excitation potential of the elements in the specimen, electrons in the element's inner electron orbitals may be ejected into higher energy orbitals. Equivalent electrons from the outer orbitals, however, consequently fall back to the vacated inner orbitals to restore atom to its normal state. When an outer orbital electron falls into the inner electron orbital, a quantum of energy equivalent to the difference in the orbital energy levels is emitted. The emitted energy manifests itself in the form of the elements' characteristic x-ray spectral line (fluorescent x-rays) which may be used to identify and quantify the elements present in the specimen[1].

X-ray fluorescence technique is routinely used in the semiconductor industry for the measurement of coating thicknesses. When a coated material is irradiated, fluorescent x-rays are emitted from both the base and the coating material. Fluorescent x-rays from the coating material

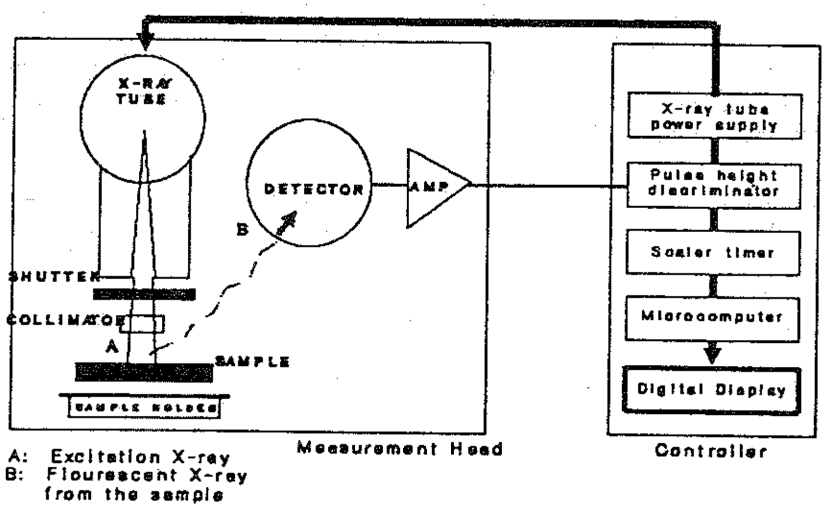


Figure 1. Configuration of SFT-156

is distinguished from that of the base material electrically by the use of an electronic circuit called the pulse height dissemination. By counting the number of pulses, the intensity of the fluorescent x-ray emitted from the coating may be measured. The intensity of the emitted x-ray fluorescence is directly proportional to the thickness of the coating. If the x-ray intensities of standard samples of known thicknesses were measured, a standard calibration curve may be prepared. The unknown coating thickness of the sample may then be interpolated from this curve from its measured x-ray intensity.

Presented in Figure 1 is the configuration of the SFT-156 machine[2]. The SFT-156 is a fluorescence x-ray coating thickness gauge manufactured by Daini Seikosha Co., LTD of Japan. It is an x-ray fluorescence machine fully dedicated to coating thickness measurement and is equipped with a microprocessor to handle standard curve calibration and accompanying statistical routines required internally such that the output already consists of the estimated coating thickness.

3. EXPERIMENTAL

Dual In-line Package (DIP) units were tin plated in three different baths which were adjusted in a manner such that high, medium, and low thickness readings could be obtained. From each bath, 10 units were randomly chosen resulting to a total of 30 samples.

A single SFT-156 X-ray fluorescence equipment was used to measure the coating thickness (in microinches) of the leads from the sampled units.

The units were numbered discretely for identification without the knowledge of the inspectors. For each unit, only the coating thicknesses of the middle portion of a specified lead was measured. The 30 units were grouped into three with 10 units each. One group had outer leads (lead 1) measured, another group had middle leads (lead 7) while the remaining group had the leads next to the outer leads (lead 4) measured (see Figure 2). The grouping was necessary to obtain wide range of thickness readings. As in any complex geometry plating situation, the plating distribution of the leads within a unit is such that the outer leads have the thickest whereas the middle leads have the thinnest.

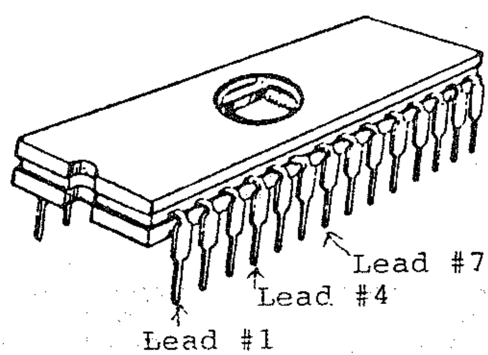


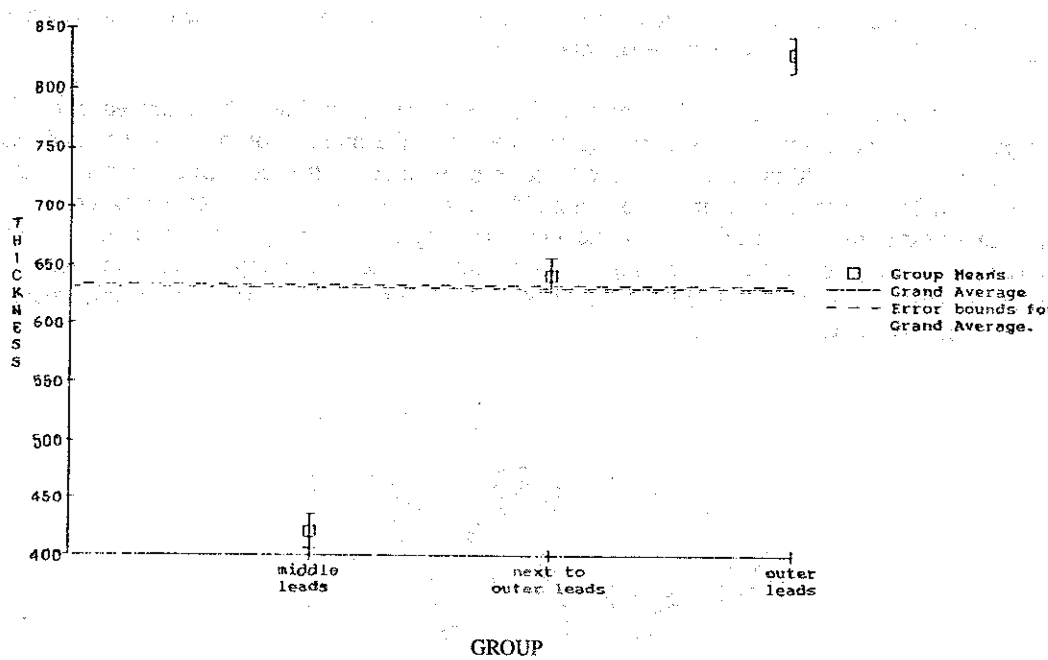
Figure 2. Dual In-line Package Unit

Three inspectors trained on the XRF equipment were asked to obtain the measurements. The thickness of the leads to be measured were randomly determined by each of these inspectors. Without moving the unit, 2 measurements were taken on each lead on the first day. This procedure was repeated on the second day. Thus, there were a total of 360 measurements for all 30 leads measured by the 3 inspectors in 2 days.

The number of units, inspectors, and replicates utilized in this experiment was limited by the resources available in the production line. In the absence of historical data gathering the XRF technique measurement error, this combination was assumed sufficient to provide pilot information for future measurement capability studies on this measurement system.

4. RESULTS AND DISCUSSIONS

The thickness readings obtained from the 3 lead locations were compared to determine the significance of the differences in mean readings of the various leads - outer, middle and next to the outer leads. Evidently from Figure 3, the outer leads exhibited the highest average reading while the middle leads exhibited the lowest average reading. The means are significantly different from each other as expected since the outer leads receive the highest current whereas the middle leads receive the lowest due to the shape of the cathode.



Error bars overlap if the difference between two means is not significant at the 5 percent level. If the error bars for the group mean overlap the dashed line, the group mean is not significantly different from the grand average. Significant differences are determined using Bonferroni simultaneous confidence intervals for all comparisons.

Figure 3. Simultaneous Comparisons Between Groups

With this result, 3 separate measurement capability analyses were conducted on each group. The details of the analysis done on the leads next to the outer leads are presented for illustration. Only a summary of comparisons on the major results for all 3 lead locations is discussed in the latter part of this section.

4.1 Analyses on the leads next to the outer leads

Figure 4 is a dot frequency plot displaying the readings of all 10 leads measured in the experiment by the 3 inspectors. The combined variability due to the performance of the inspector and equipment in each lead is represented by the lengths of the lines on each box while the total measurement error of the thickness readings per lead is given by the lengths of the rectangular boxes; the longer the lengths of these lines and boxes, the larger the variability.

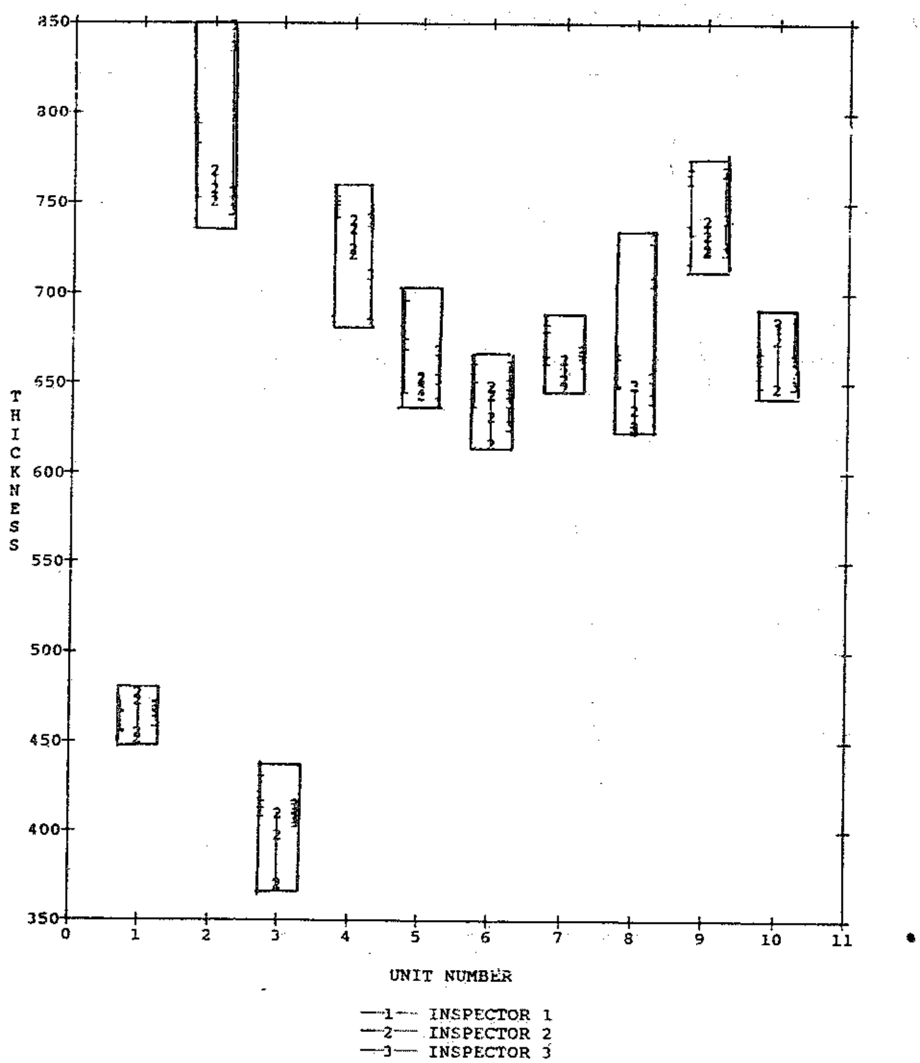


Figure 4. Dot Frequency Plot

To illustrate, the thickness readings of the leads from units 2 and 8 have the largest measurement error particularly attributed to the variability of the replicated readings taken by inspector 3. On the other hand, the readings of the lead from unit number 1 has the least measurement error with all inspectors having almost the same variability.

The variations in the lengths of the boxes in the different leads is an indication of inconsistencies in the readings per lead. In statistical terms, this is the presence of interaction in the variables being considered.

To further understand the interaction, a graph of the average readings of the 3 inspectors on each lead is provided in Figure 5. The interaction graph shows that there exist no systematic error among the 3 sets of readings. No inspector consistently has the highest readings over all leads measured. Also, there are leads where the differences in the averages are significant while there are leads where the differences in the averages are nil.

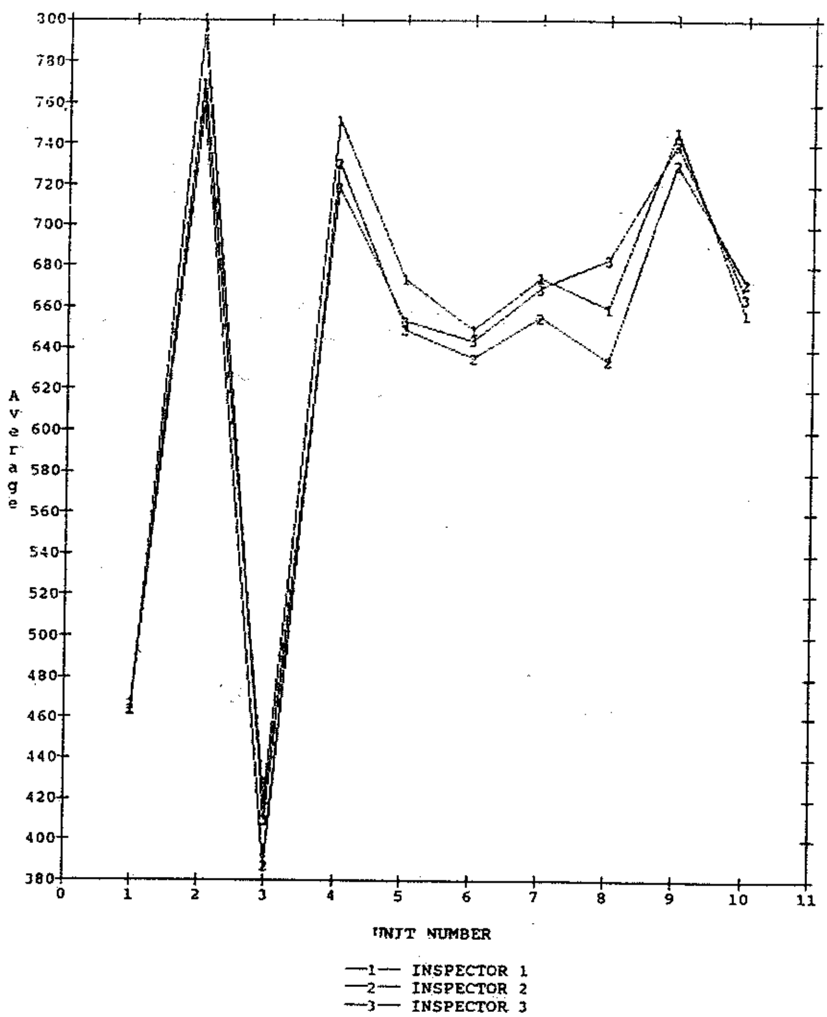


Figure 5. Interaction Graph

The standard deviations of the replicated readings of the inspectors per lead are plotted on Figure 6. This graph is on a control chart format with an upper control limit. If a point falls beyond this limit, then that point is considered as an outlier and needs to be investigated. In this particular case, there are 2 points falling beyond the upper limit and both are standard deviations of the readings by inspector 3 on the leads of units 2 and 8. This problem has been detected in the dot frequency plot discussed earlier. No data entry error had been found to have caused this outlier to occur.

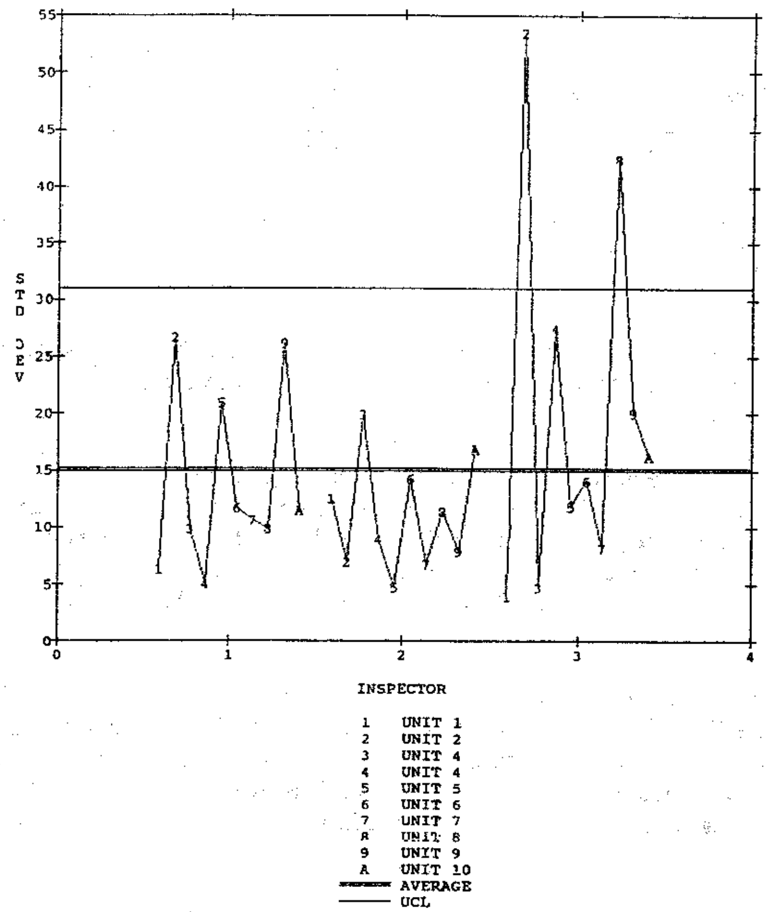


Figure 6. Standard Deviation Chart (Lead for each Inspector)

Thus, for any thickness reading (y) obtained in this experiment, the following model is used:

y = overall mean + lead effect + inspector effect
+ insp*part effect + insp*lead*day effect
+ day-to-day effect + replication error

The Analysis of Variance (ANOVA) Table for the model is given below.

Table 1
Analysis of Variance

Source of Variation	Degrees of Freedom	Mean Square	P-Value
Inspector	2	2636.4	0.0408*
Lead	9	165978.5	0.0001*
Day	1	725.2	0.3175
Inspector*Lead	18	595.9	0.0001*
Inspector*Lead*Day	18	686.2	0.0116*
Error	71	257.3	

* significant at 5% level

As expected, the lead to lead variability is significant since the 10 units were randomly sampled from different bath conditions. However, this significant variability is not a contributor to the measurement error.

The day to day variability is insignificant from the p-value reflected in the ANOVA table. However, the significant variability due to the days has been covered by the 3-factor interaction. Referring back to the dot frequency in Figure 4, it is evident that the differences in the replicated readings are not constant. The differences are due to the combined variability of the equipment and the inspector's ability to accurately focus the scope on the same location as the first reading after moving the unit.

The significance of the inspector variability and the interactions in the ANOVA is an implication that the XRF system is sensitive to the inspector technique of measuring the thickness of the leads. Since the procedure for measuring the thickness of a lead involves the focusing of the scope in the XRF at the middle portion of the lead, it is expected that inconsistencies among and within the readings of the inspectors will be significant due to the differences in eye vision of each inspector.

In this model, all sources of variation except for the lead variability are components of the measurement error. These components can be summarized into 2 major components: reproducibility and repeatability. To differentiate, the variability in the average thickness readings obtained when several inspectors measure the same leads using a single measurement equipment is known as reproducibility. On the other hand, repeatability is the variation in the measurements obtained by the same inspector on the same lead at different occasions. Therefore, variabilities due to inspector and interactions are the basic components of reproducibility while the variability due to the replicated readings obtained in 2 days is referred to as repeatability.

Having verified the significance of these components, the estimate of the magnitude of error to be expected out of these components and the whole measurement system will be a relevant information. The error in this analysis is quantified using standard deviation estimates.

Table 2 provides the 90% confidence interval and point estimates for the standard deviation of each component of the measurement error. The 90% confidence intervals are necessary to account for the sampling error.

Table 2. 90% Confidence Interval Estimates for the STD DEV of the Components of Variance (in microinches)

COMPONENT OF VARIANCE	LOWER 90% LIMIT	POINT ESTIMATE	UPPER 90% LIMIT
REPEATABILITY	14.0	16.1	18.9
REPRODUCIBILITY	10.4	15.5	32.4
MEASUREMENT	17.7	22.3	30.6

The estimated average measurement error for the XRF technique is 22 microinches. The repeatability of the measurement system has been estimated to range from 14 to 19 microinches while the variability due to the differences in the inspectors can range from 10 to 32 microinches. Though the repeatability is the combined variability of the performance of the inspector and equipment, the magnitude of error reflected in this component is mostly attributed to the equipment error. The manufacturer's guarantee is 20 microinches.

The wide range of the interval estimate for the reproducibility is brought about by the small number of inspectors chosen in the experiment. To be able to accurately estimate this component, future experiments must include large number of inspectors. On the other hand, the interval estimate for the repeatability is relatively accurate given the number of replicates used.

4.2 Measurement Capability Indicators

With these estimates, measurement capability indicators can be obtained to assess the accuracy of the system over time. There are two indicators available though its usefulness depends on the purpose for taking the measurements. One indicator is the Signal-to-Noise ratio (SNR) which is the ratio of the process variability and the measurement error. The SNR is meaningful if the measurement is obtained as a monitor to help detect any shifts in the process.

The other indicator is the Process-to-Tolerance (P/T) ratio which is the ratio of the measurement error and the tolerance spread. This ratio is applicable if the measurements are compared to a bilateral specification particularly to screen out units with off-spec thickness readings.

An excellent measurement system has an SNR value greater 10 and P/T ratio value of less than 10%. On the other hand, an unacceptable measurement system has SNR value of less than 3 and P/T ratio of greater than 30%[3]. These figures are rules of thumb and can be altered as per the user's judgement. A large SNR value is an indication that the measurement system is highly sensitive to any process change while a small P/T ratio is an indication that the system can discriminate off-spec readings from good readings.

Since the estimate of the variability in the thickness readings of the leads is not representative of the true process variation, the SNR value for this experiment is meaningless. The point and 90% confidence interval estimates for the P/T ratio computed are:

Lower 90%	Point Estimate	Upper 90%
14%	16%	19%

This means that, on the average, the measurement error consumes 16% of the tolerance spread of 800 microinches. Comparing to the goal of less than 10%, it can be said that the current measurement system needs improvement to be effective in screening out leads with off-spec thickness readings.

4.3 Comparison of the results of the Meascap on the 3 groups of lead locations

The results of the analyses on the middle and outer leads are comparable to the results of the analysis on the leads next to the outer leads. The summary of the estimates of the components of variance from the 3 groups is given in Table 3.

Table 3. 90% Confidence Interval Estimates for the STD DEV of the Components of Variance

COMPONENT OF VARIANCE	LOWER 90% LIMIT	POINT ESTIMATE	UPPER 90% LIMIT
	(Outer leads - High Thickness)		
REPEATABILITY	1.25	14.2	16.5
REPRODUCIBILITY	12.3	15.9	22.9
MEASUREMENT	18.2	21.3	26.0
	(Next to the outer - Medium Thickness)		
REPEATABILITY	14.0	16.1	18.9
REPRODUCIBILITY	10.4	15.5	32.4
MEASUREMENT	17.7	22.3	30.6
	(Middle leads - Low Thickness)		
REPEATABILITY	13.5	15.2	17.3
REPRODUCIBILITY	7.7	10.7	18.4
MEASUREMENT	16.2	18.6	21.8

Although the absolute values of the point estimates of the overall measurement error on the three groups differ, these estimates are not significantly different from each other since the confidence interval estimates for the components overlap.

From these estimates, one can safely conclude that the measurement error of the XRF technique does not vary significantly over the wide range of thickness readings (300-1000 microinches).

5. CONCLUSIONS AND RECOMMENDATIONS

XRF measurement system is a quick method of obtaining tin thickness measurements and is excellent for process control when the variations in the tin thickness readings are more than 200 microinches, based on the SNR value of 10. However, the system can still detect shifts in the thickness process in the order of 80 microinches based on a barely acceptable SNR value of 4. In this case, to compensate for the relatively large measurement error, it is suggested that multiple readings be taken for each lead being measured. For processes with smaller variations, more sensitive methods of thickness measurements such as cross-sectioning are required. With the measurement error consuming about 16% of the process tolerance spread, it is expected that the system can still discriminate good from off-spec thickness readings but not very well.

It has also been found that this system is sensitive to the inspector technique particularly in focusing the scope to the area on the lead where the reading will be taken. Thus, ensuring a good training for all users can reduce the error due to the measurement system.

Finally, the measurement capability study on the XRF technique must be done periodically since the equipment degrades and the inspectors change over time. A study may also be conducted after improvements in the system have been implemented to check the impact of the said programs. This is essential for any measurement system especially if the system is playing a critical role in maintaining quality in the plant.

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