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MICRO-FOCUS X-RAY IMAGING

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INTRODUCTION

The acceptance of surface mounting in the electronics industry has been slowed by problems with component availability, electrical testing, and inspection. Industry suppliers and users have been working to solve these problems, and these problems are easing. Component manufacturers are offering substantially more devices in surface mountable packages. Automated test equipment vendors are offering test fixtures for surface mount circuit boards. And just recently, solder connection inspection has been automated through a "partnership" effort with a major electronics manufacturer. The result achieved in this successful first installation is the subject of this paper.

THE NEED FOR SOLDER QUALITY INSPECTION

Surface-mounted devices are held in place on the circuit board by their solder connections. The same situation occurs on plated-thru-hole circuit boards. However, with surface mounting, there is no solder plug surrounding a pin thru a hole in the circuit board to give the connection added strength. Instead, the solder alone bonds the device to the circuit board, as shown in figure 1. The electrical integrity of the circuit board is totally dependent upon the structural integrity of the solder connection. This issue of structural integrity, plus the large numbers of solder connections on each circuit board, is the impetus for automating solder connection inspection.

Surface mounting makes more electronic products man-portable or mobile in vehicles. With this portability or vehicular mobility comes shock, vibration, and extremes of temperature. Shock, vibration, and temperature approach or exceed levels that were previously associated only with military electronics. These higher stress levels must be sustained by the smaller solder connections characteristic of surface mounting. Numerous experts have cited how surface mounted solder connections are disposed to fatigue and creep failure.

STRESS AND ELECTRICAL TESTING

The structural integrity of solder connections can be assessed to some degree with "shake and bake" stress testing. However, this type of testing confronts the risk of wearing out the product before it ever reaches the customer. Further, the electrical testing that is used with "shake and bake", as well as that usually performed in regular manufacturing quality assurance, detects only the "open" or "short" conditions. Stress testing typically does not expose the structurally marginal connections that still conduct, but are long term candidates for failure, such as:

- insufficient solder
- poor wetting
- excess solder or lead projection
- device or lead off position
- unwanted solder balls or splashes
- device tilted relative to the board
- porosity in the solder connection

VISUAL INSPECTION

Visual inspection can detect gross defects, such as missing devices, bridges outside the devices, the absence of solder fillets, and non-wetting. However, visual inspection is qualitative rather than quantitative---it does not measure the extent to which a defect exists. Also, visual inspection relies upon the external appearance of the solder connection to infer its internal structural integrity. And with surface mounting, the solder connections are partially or fully underneath the devices, making visual inspection impractical.

STRUCTURAL INSPECTION

Structural inspection is not a new problem. For years, aerospace and casting manufacturers have used X-ray inspection to examine the structural integrity of castings for airframes, engines, and transmissions. Since solder connections are a "casting" formed by the surface tension of the molten solder and the surfaces of the device and the circuit board, X-ray techniques will work for solder connections. The keys to making X-ray techniques viable for solder connection inspection are to:

1) speed up the X-ray imaging process
2) radiation from damaging electronic components
3) improve X-ray imaging to resolve 0.001 inch features
3) automate inspection to achieve fast, accurate results
4) make the techniques usable in the production line

DEVELOPING A SOLDER QUALITY INSPECTION MACHINE

In 1984, we became aware of the need for structural inspection of solder connections in surface-mounted electronics thru a customer, and developed the machine shown in figure 2 specifically for solder connection inspection. This machine took "flash" X-ray images of each device on the circuit board to keep radiation from damaging the device, and automatically inspected the "structure" of each solder connection according to a "rule set" that took into consideration:

- o the type of device (PLCC, SOT, LCC, etc.)
- o the shape of the pad on the circuit board
- o the amount of misalignment allowed between the device and the circuit board
- o the range of solder connection thickness allowed
- o the range of solder connection shape allowed
- o the amount of porosity allowed

This first machine administered a maximum dose of 5 RAD(Si) to each circuit board, was designed to "see" features as small as 0.002 inch in size, and used images like the one shown in figure 3 to inspect each solder connection. A schematic for this first machine is shown in figure 4. In operation, the machine used an electrical X-ray source to project a collimated beam of X-rays up through a 1" by 1" area of the circuit board. The X-ray shadow image of the solder connections was projected onto a fluorescent screen just above the circuit board. This screen converted the X-ray image into a visible light image, which was viewed by a high-resolution video camera through a first surface mirror to keep the camera and optics out of the X-ray beam. The video image of the solder connections was input to a digital image processor that performed the actual inspection under the direction of a set of programs in an IBM Personal Computer.

RESULTS ACHIEVED WITH THE FIRST MACHINE

In mid-1985, this first machine was installed in a surface mount production line to inspect 1000 circuit boards per day with J-leaded surface mounted ICs. Each circuit board had 252 solder connections, and inspection time per circuit board was 30 seconds. Since the customer's production line operated seven days per week, this first machine and its software have inspected more than 200,000 circuit boards $\cong 63 \times 10^6$ joints. This large production volume has forced us to make our inspection programs effective for the wide variations found in production solder connections made with vapor phase reflow.

The defects identified by this first machine have been (and are today):

- void (absence of solder joining lead to pad)
- insufficient solder (including porosity)
- bent lead (off position from pad)
- leads touching (producing a short without a bridge)
- solder bridge
- device off position (skewed or shifted)
- device missing from board

These defects are identified accurately and repeatably, and our customer is pleased with the performance of the machine (particularly since it has already paid for itself). However, there are some caveats on inspection accuracies.

Solder bridges and missing devices are practically always found, since they represent extreme conditions. Insufficients, bent leads, voids, and off positions are questions of the degree to which the defect is present. Through manual re-screening of automatically inspected circuit boards, we have learned that these defects are found roughly 95% to 99% of the time. The range from 95% to 99% is largely attributable to the variability of the human inspectors used to perform the re-screening. Inspectors do make "bad" calls on occasion. A more important facet is the relationship we found between increased defect detection and increased "false rejects", product rejected as bad when it is truly good.

THE IMPORTANCE OF ACCEPT/REJECT THRESHOLDS

Figure 5 shows two overlapping distributions that help explain this relationship. The horizontal axis is a "measure of quality" that is a composite of many measurements of the size and thickness of each solder connection. The vertical axis is the number of solder connections with that measure of quality in a batch of boards. The accept/reject threshold determines whether a solder connection is accepted as good or rejected as bad. Solder connections to the left of the threshhold are rejected as bad. Solder connections to the right of the threshhold are accepted as good.

This relationship between defect detection and false rejects can be seen in Figure 5. As the accept/reject threshold is moved to the right, more and more defects are detected until practically none escapes inspection. However, as defect detection grows in effectiveness, so does the number of good connections (the left "tail" of the "good" distribution) that will be falsely rejected as defective. This results from the overlap of the "good" and "bad" solder connection distributions, and reflects reality. We have found that the characteristics of marginally good solder connections significantly overlap those of marginally bad solder connections.

As a result of the relationship between the accept/reject thresholds and the economics of our customer, the accept/reject thresholds for the first machine have been set up to detect roughly 97% of all defects while making fewer than 5% false rejects. These performance levels are far better than those achievable with inspection personnel. And, inspection by our machine is done before electrical testing to increase the effectiveness of electrical tests. For other customers with a different manufacturing process, and different costs for inspection, rework, scrap, and escape of defects, different accept/reject threshholds would be necessary to achieve the best economic return for their circumstances.

THE "STRUCTURAL" SOLDER QUALITY STANDARDS PROBLEM

As an aside comment, the requirement for flexible accept/reject thresholds, when coupled with the wide variations found in production solder connections, and the absence of complete information about what a good solder connection "looked like", almost prevented us from delivering a satisfactory working machine. Fortunately, our customer was willing to spend considerable time and money developing their own structural standards for what made solder connections good versus bad. This required stress cycling hundreds of circuit boards, analyzing each failure to establish causes, and then proceeding with production while monitoring production items for in-the-field failures on an on-going basis. All this work entailed considerable investment, and resulted in standards that are not consistent with present visual inspection standards. When structural standards are developed for other products, such as avionics, we feel these standards will not agree with existing visual inspection standards. Since a substantial beneficiary of these new structural standards would be the military, funding for standards development should be allocated as soon as possible, particularly in view of the increasing concerns over the structural viability of leadless surface mounted devices. Based on the experience of our customer, where practically no field failures now occur, these new standards would clearly help reduce in-service failures. And, our customer's product environment is 3+ G's of shock and vibration, ambient temperature from -40 F to +125 F, and humidity from 0% to 100%.

CONCLUSIONS

It is difficult to extrapolate general savings rules from a single installation. However, we have shown with our first installation that automated X-ray inspection can dramatically reduce:

- the costs of inspection
- the incidence of unnecessary rework on good boards
- the recycling of boards thru rework as additional defects are cited
- the costs of scrap by minimizing rework
- the escape of defective boards
- the incidence of defects

This last point is an often overlooked major benefit area. With the quantitative quality data that is a by-product of automated X-ray inspection, you can control your manufacturing process to make a better product. Our first machine was installed in a new manufacturing line with completely new equipment. During process start-up, it was discovered that our machine could help set up the solder paste screen printer and reduce the incidence of voids, bridges and insufficients. During production, our machine continues to monitor paste printer performance by noting the incidence of bridges and insufficients. When our defect reports show an increase in bridges or insufficients, the customer's personnel know how to adjust the process back into control. As a result, our customer has been able to achieve a significant increase in yield.

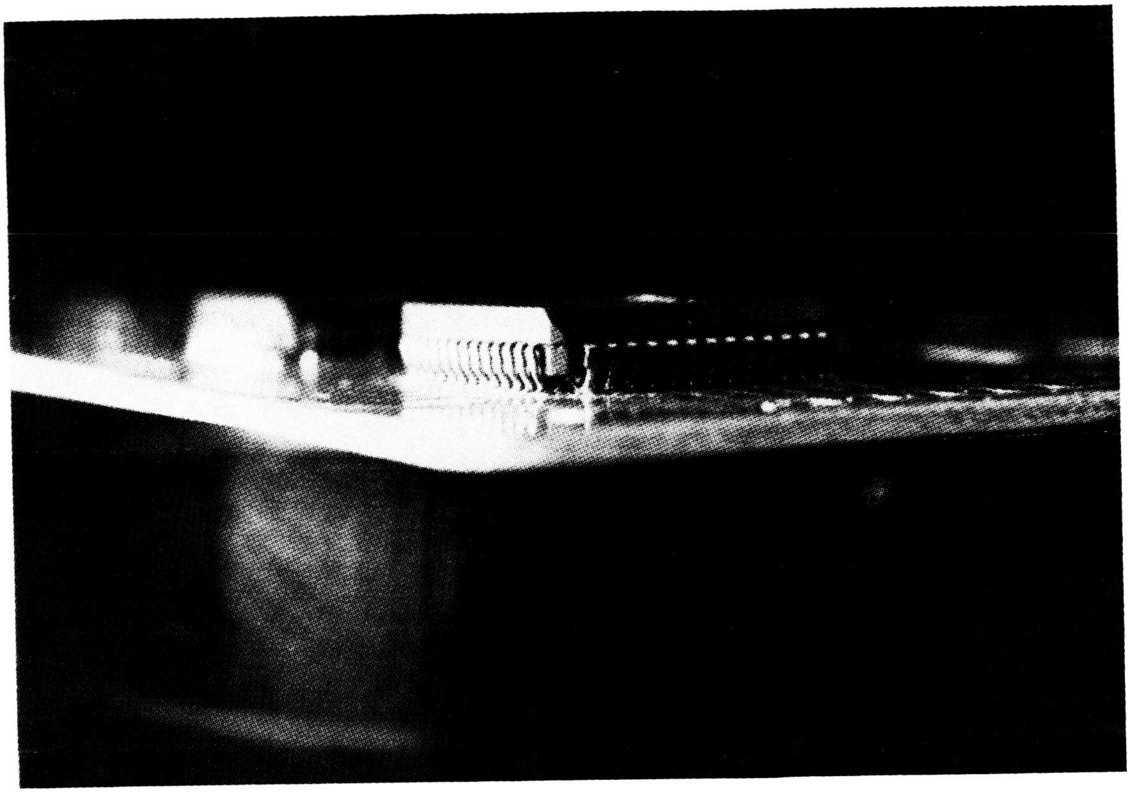

Figure 1. Visual image of PLCC on a circuit board.

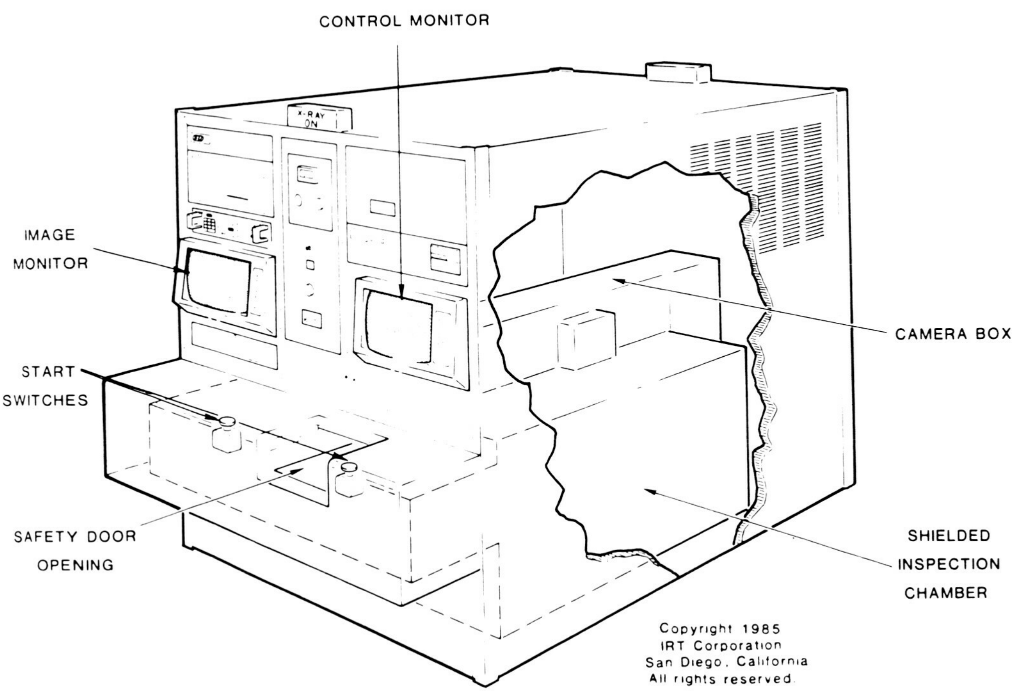

Figure 2. Line drawing of first inspection machine.

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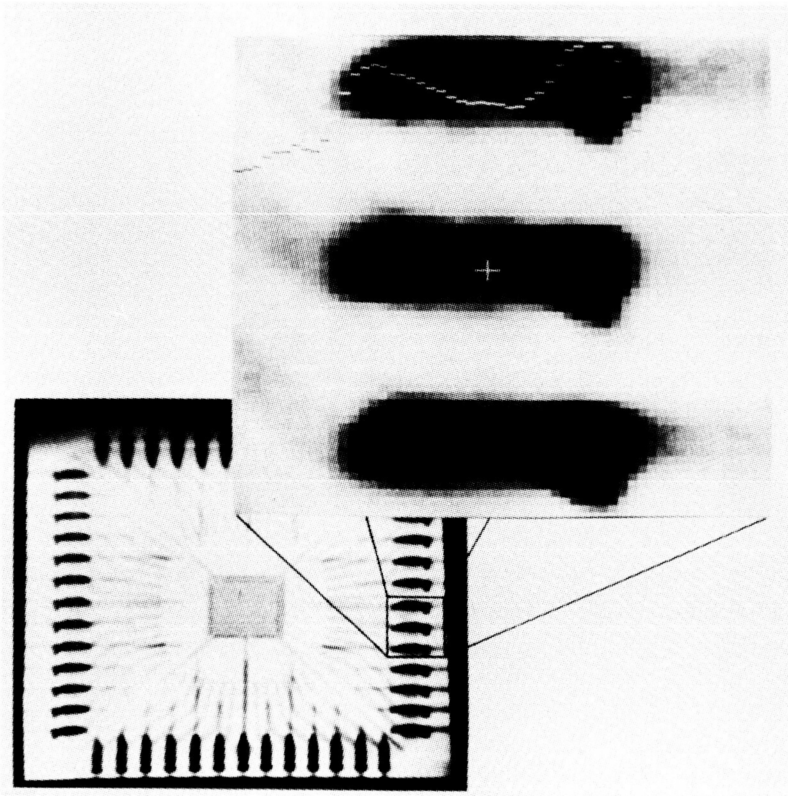

Figure 3. X-ray image of PLCC.

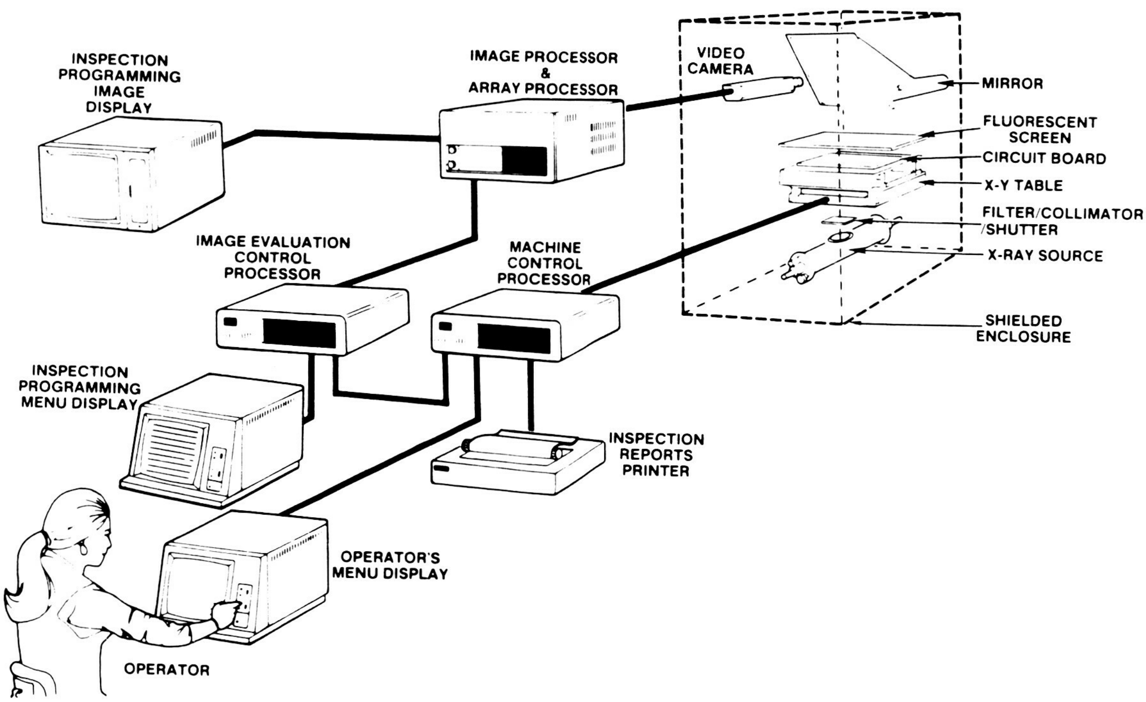

Figure 4. Schematic for first inspection machine.

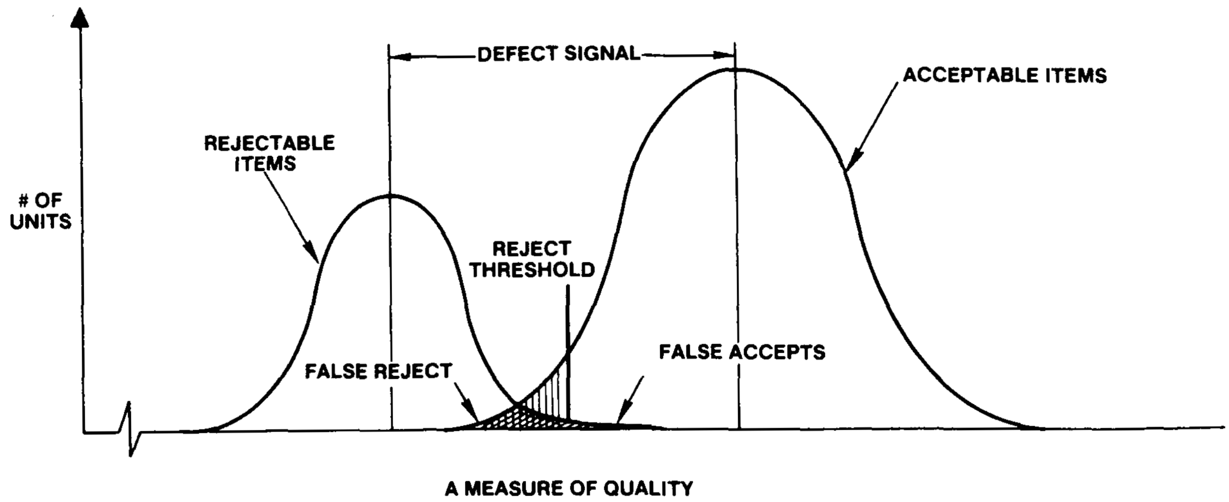

Figure 5. Distributions showing solder connection quality.