Using HFE Principles to Reduce Type Two Error Associated with Termination Defects from SMD Process

By David Fissell

Introduction

Project focused on reducing the risk of type 2 error associated with operator inspection task related to poor termination quality following the surface mount electronic assembly process. Type 2 errors, results in external failures, are the most costly for manufacturers and any reduction in type 2 errors goes directly to the bottom line. Due to project time constraints and the desire to observe measurable improvement, termination defects were chosen for the purpose of understanding the inspection process. Signal detection theory was used to understand the inspection process. A PDSA approach was used as a framework for the project. The current situation, the interrelationship between operator inspection work demands, work arrangement and environment, as well as workstation and tooling were defined and analyzed as the basis for identifying improvement opportunities. Improvement opportunities, countermeasures, were identified and put in place where possible. However, effectiveness of countermeasures will need to be monitored into the future to determine effectiveness of project deliverables and further improvements.

Background

Surface Mount Electronic Component Placement (SMD) Process

A printed circuit board (PCB), a wiring harness, receives solder paste at surface mount component pads through an aperture in a metal stencil during the paste deposition step. With solder paste on top of the surface mount component pads the PCB passes through a CNC SMD machine placing the electronic components optically and lightly into the solder paste. At this placement step, solder paste tackiness holds the components to the solder paste. The PCB then moves through a reflow oven where the solder joints are formed between components and PCB pads. After the reflow step the PCB with components soldered to pads is called an electronic assembly (PCA). (Fig. 1) SMD process controls are achieved through paste deposition method and analysis, SMD operator training, reflow thermal profiling, and statistical process control of key process parameters. However, current state of process controls is incapable of reducing defects to a zero defect level. The customer expects no external failure. Therefore, customer product processed through the SMD process is verified as conforming through automatic optical inspection (AOI), x-ray inspection, and operator visual inspection.

Paste Deposition → Placement → Reflow → Verification

Figure 1: SMD Process

Failure Modes, Actions, and Status

Poor termination (solder joint) quality and component placement errors represented at least 90% of the defects observed internally and approximately 96% of the external failures related to the PCA manufacturing process. Component damage as a defect represented less than 5% of total defects observed internally and is split between supplier received (> 98% of defects) and process caused. Supplier received component damage is primarily internal and caught through assembly electrical testing and voltage checks on CNC SMD machine. External component damage, whether from supplier or process will cause the CNC SMD machine not place or component will not reflow resulting in both cases a missing component caught by AOI machine. The risk for the assembly manufacturer is returned material (product) requiring troubleshooting due to a premature life electrical failure at customer site. In 2007, all premature life electrical failures returned by customer where customer did not want to pay for electrical assembly testing were due to component failures that electrical testing could have avoided. Other defects occurred; however, these defects are unusual and occur as isolated events, for example wrong label attached to PCA (one incident in 2007).

Poor termination (solder joint) quality occurred at least 75% of total defects observed internally in 2007 and is partitioned between non-wetted joints (no solder paste) and solder bridges/shorts (improper thermal profile). Operator inspection is the primary means of external failure avoidance and it occurs as a sorting function mostly several days to greater than a week after SMD process. In 2007, 25% of external failures – type 2 error - were due to poor termination quality. From the data, operators performing the inspection task have much easier time in visually searching and detecting poor termination quality defects on a PCA.

Component placement error represented less than 15% of total defects observed internally in 2007 and is split between the wrong component placed and the wrong placement of a component (orientation error). Wrong component placed occurs infrequently (less than 5 times per year), but when it occurs, it is due to poor configuration management and resulted in 100% type 2 error implying machine and manual search and detection methods do not stop this type of defect. Orientation error is due to improper CNC SMD machine program, components not having same alignment at CNC SMD load, or operator hand-places component incorrectly. Operator inspection is the primary means of external failure avoidance and like poor termination quality, occurs as a sorting function several days to greater than a week after SMD process. In 2007, over 60% of external failures were due to orientation errors. From the data, operators performing the inspection task have a much more difficult time searching and detecting orientation errors.

In both poor termination quality and orientation error current AOI machine technology has not been capable of removing external failure risk with 100% reliability forcing electronic assemblers to rely on operator visual inspection. As component density increases and size of components shrink, optics becomes more a magnifier requiring an inspector to sort through a large number of false errors (type 1) increasing inspection time with little to no reduction in type 2 error. Additionally, optics is incapable of checking all types of termination joints: pads located below the component periphery requiring an operator to check with a magnifier light or microscope. Current AOI machine optics has difficulty with contrast sensitivity, anything other than black and white contrast, a necessary function to detect orientation marks of various colors or features on a component. It is these various colors and features on the component that determines how the component should be placed on the PCB. Therefore, until AOI technology can reduce risk of type 2 error associated with solder and orientation defects, electronic assemblers will continue to rely on operators for the inspection task.

Scope

Though termination defects have approximately 150% less external failures, type 2 error, when compared to orientation error, they do comprise 75% of the internal process problems. Termination defects on a total cost basis are my company's highest cost of poor quality. If this project can reduce the amount of termination process defects, the number of external failures associated with termination defects should drop as well. Additionally, termination defects can only be spotted with any reliability using operator inspection. From the data, inspectors have a must easier job detecting termination defects than orientation defects; this may be due to the large volume of termination defects observed focusing inspectors attention on termination defects over orientation defects. For the above reasons, I chose termination defects as the focus of this project; for I desire the largest potential financial gain for my efforts.

Problem

In 2007, poor solder joint quality and orientation errors resulted in approximately 96% of my company's external failures at an approximate cost of over a half million dollars. Both of these defects resulted in 254 external failures requiring engineering time to deal with the customer care request instead of process controls improvement; additional costs associated with returned product, rework and scrap; as well as customer dissatisfaction and lost sales. Financially, any improvement reducing type 2 errors, external failures, is a gain to the bottom line. Contributing causes are as follows:

- The SMD verification process was combined with all other inspection processes, in an inspection department detached from the SMD department by 200 feet. The facility layout was based on product flow: inspect, sort and rework prior to shipping product to customer. This type of layout supported a reactionary approach instead of a proactive approach to product and process issues: sort product instead of fixing the process causing the nonconforming product. Additionally, defect data related to a product and process lacked real time feedback; defect data was several days to greater than a week old providing little to no value for product and process improvement.

- Inspection task took a Taylor approach, select the right people to perform the inspection task and improve performance by punishing the operator for missing the defect for the inspection task had to be performed improperly. The alternative is to design inspection work centered on the robustness of human's cognitive capabilities and limitations as well as providing a comfortable and safety work environment.
- Inspector training and inspection feedback to improve top – down processing is poorly defined. Inspection involves a human visual search and detection processes where defects are observed as symbols, signs and signals. Inspectors require knowledge of what is a termination defect; cognitive engineers call these signs. Inspectors require rule based knowledge, what to do under various situations; cognitive engineers call these signals. The inspector must understand the degree of issue: target condition, acceptable condition and non-conforming condition. Inspection discrimination and criterion capability is trained through feedback of the inspection process like iterative learning process. The ability to process inspection visual data (sensory – motor function) is the skill; cognitive engineers call these symbols. (Rasmussen) For inspectors, attention-to-detail testing similar to recognition tests given to mail carriers are good personnel selection tools for nurturing inspection skills. (Raz)

Root cause is the electronic industry still lives in the shadow of why did you miss the defect instead of why did the defect occur in the first place. The process feedback necessary to improve process capability and inspector capability, and ultimately operator capability is poorly defined. The importance of process feedback is not understood. Therefore, the goal of the project, the deliverables, will be to achieve real-time data with engineering correcting the reason for the defect at time of occurrence, a robust inspection method where feedback is provided to improve inspectors' top – down processing, as well as a comfortable and safe inspection station. If these deliverables are achieved I expect a decrease in termination defects both internally and externally.

Current Situation, Analysis and Countermeasure

Workstation and Tools

The workstations are not standardized; each inspector has been allowed to personalize the workstation. Inspectors were observed through an activity study using their microscope as the dominant inspection tool instead of magnifier light. Industry standards (IPC-610) suggest performing the inspection with a magnifier light and using the microscope only as a referee. Inspectors stated, "They could not see fine pitched parts with the magnifier light, so they need the microscope." Additionally, when inspectors use the microscope they hunch-over to see potentially risking neck, back and shoulder problems. Microscopes have little to no physical positioning adjustments.

I conducted a lighting survey. I measured the 1.75X adjustable magnifier lights in the plant using an illuminance meter; 21 of 23 magnifier light sources required immediate light bulb replacement. After replacement of the fluorescent bulb in the magnifier lights I measured the light at 150 lx using an illuminance meter approximately 1 foot away from the light source. The work piece at this magnification will be approximately 8 – 10 inches from the bottom of the magnifier lens. This amount of target light is sufficient based on Cornell's Lighting Visibility Calculator (www.ergo.human.cornell.edu/AHProjects/VisibilityCalculator.html). I measured microscope ring lights and determined it was necessary to replace all light bulbs. Microscope ring lights are adjustable. After replacement of microscope ring lights, I measured the target light from 100 to 250 lx with an illuminance meter approximately 1 foot away at lowest and highest setting. This is an acceptable target lighting level for a work piece that will be evaluated about 2 to 3 inches below microscope lens. I established a semi-annual lighting survey preventive maintenance requirement for magnifier, microscope, and workbench lighting sources.

The relationship between tabletop, reach, chair, and foot rest was checked. With the lack of a standardized workstation inspectors are over-extending their upper body and arms to reach items on the workbench potentially risking neck, back and shoulder as well as arm problems. The chairs being used have little adjustment causing the inspectors' trunk to tabletop to vary considerably increasing the risk of lower back issues. New ergonomic ESD adjustable chairs were purchased to reduce the risk of lower back issues. Additionally, there is no foot rest for the inspector underneath the workbench increasing the risk of foot and ankle issues. The new inspector's workstation has an adjustable foot rest under the workbench. The combination of the new chair and foot rest should reduce the risk of the swelling of inspectors' feet.

The tabletop was standardized as follows: (see fig. 2)

- Microscope was centered on the table attached to a stand allowing the operator to adjust the height of the scope to eye level. This adjustment reduces the risk of neck and shoulder issues by minimizing the need to hunch over the microscope. Additionally, the microscope was attached by a swivel clamp to the bar projecting outward in the medial plane allowing the operator to adjust microscope to the eyes thus reducing the need to bend the neck. The microscope swivels at the base allowing the operator to move microscope out of the effective work area but within the inspector's reach.

- Knobs were attached to the right side of the workbench, within arms reach, below table top to allow inspector to adjust ambient and target lighting. Ambient lighting was provided directly over the bench. On each side of the work table is an adjustable target light. The 2.25X magnifier light is mounted at the back of the work table and to the left of the microscope. The magnifier light and both target lights are within the arms reach zone.

- Two 17 inch LCD flat screen computer monitors, in tandem, were placed to the far right of the microscope on an adjustable stand. The adjustable stand allows the operator to set distance from eyes to screen as well as tilt capability for accommodation. The LCD screens have a matte finish reducing risk of glare. The keyboard is currently placed within the reach of the inspector at the right side. A rest pad is attached to the front of the keyboard.

- Solder iron and tools are on the top of a sliding table, within inspector's reach, and located between microscope and computer screens. The operator can pull the sliding table out to perform rework and push the sliding table back when not in-use. A fixture to hold the PCA while performing termination rework is within inspector's reach to the left of the inspector.

- Forearm rest pads are placed at table's edge to reduce arm fatigue while performing inspection task.

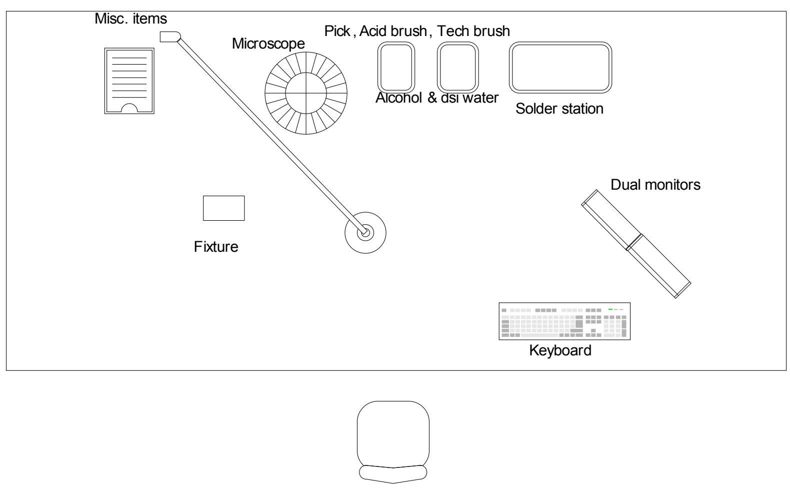

Fig.2 Mockup of Inspector Workstation

Operator Inspection Work Demand

For the purpose of this project, inspection is defined as the evaluation of an electronic assembly by an operator for poor termination quality after the SMD process. Inspection is a cognitive task combining quality of inspectors' visual acuity and color perception; ambient and target lighting condition; training and experience level with electronic assembly conformance criteria; ability to maintain attentiveness (attention-to-detail) throughout the inspection task; as well as the ability to discriminate termination defects against a mental model criterion.(Raz) Inspection involves processing visual information through the long-term memory mental models in a compare and contrast fashion; however, an inspector's ability to efficiently and effectively do this is impacted by inspector's state of working memory and attentiveness.(Wickens) Job cues can help to amplify working memory and attentiveness attributes.(Wickens)

Our inspectors receive a three day, intense, electronic industry workmanship standards training class at initial assignment to inspection department and every two years thereafter. (IPC-610) Training effectiveness is measured by having to score 90% or greater on a multiple choice, open book, industry test. This type of training meets the knowledge or sign side. Proficiency was determined by having a senior, more experienced inspector check the work of a less experienced worker. Over time, mostly less than 90 days, the less experienced inspector was considered experienced and no longer required a work check. Feedback on quality of inspection no longer took place. Signal's training is not occurring due to lack of inspection feedback. To change this situation the following was done: our inspectors were given, and will continually be given, proficiency tests to evaluate inspectors' inspection capability as well as inspection feedback from engineers related to the real-time defect action messages. Moreover, skills checks were not being conducted: our inspectors were not required to take visual acuity and color perception tests; and no test was administered to check attention-to-detail performance. All new inspectors will be required to take a test to check attention-to-detail performance as well as visual acuity and color perception tests.

To better understand this cognitive, search and detection, inspection task I designed a proficiency exam to determine inspectors' inspection capability using 5 different PCAs with 10 known termination defects to determine inspectors' type 1 and type 2 error responses. I used signal detection theory with operator response curves as my measurement tool and risk assessor. (Raz) Each proficiency exam set had a new set of 5 different PCAs. The inspectors were provided only 10 minutes to complete the exam. The results and analysis of the proficiency testing before workstation changes are as follows:

- First proficiency test was performed at inspector's original workstation, no modifications made, using only the 1.75X adjustable magnifier light. The exam was administrated by telling each inspector to only look for termination defects. Eleven inspectors were tested under these conditions; they had an 85% hit and 10% false alarm rate. When questioning the inspectors on the missed items and the reporting of the false alarms the general consensus was these errors were due to not being able to use the scopes.
- Second proficiency test was conducted under the same conditions as the first proficiency exam except the inspectors were allowed to use a 10X microscope. Of the eleven inspectors tested under those conditions, they had a 96% hit and 32% false alarm rate. When questioning the inspectors on the high false alarm rate general consensus was it was better to be safe than sorry. The missed item was due to inspectors' criterion associated with acceptable and unacceptable condition. General consensus was yes it was a defect; however, it was viewed as acceptable due to mixed feedback from supervisors and engineers.
- Third proficiency test was conducted under same conditions as second proficiency test except inspector was told to fix the defect observed and then a second inspector would

check the acceptability of the rework. Of the eleven inspectors tested under those conditions, they had a 92% hit and 8% false alarm rate. Second inspection of the rework by the eleven inspectors had a 100% hit and 4% false alarm rate. Our inspectors are capable of performing their own reworks for termination issues; a practice currently reserved for a rework technician. If inspectors have to fix what they find their false alarm rate drops considerably. Our inspectors are dependent on microscopes for performing termination inspections, which goes against industry directives.(IPC-610)

Visual acuity and color perception testing was given to the eleven inspectors. Seven of the eleven inspectors required new prescriptions for glasses. The company paid for working glasses for the seven inspectors requiring new eyeglasses. The eleven inspectors passed the color perception test.

The next round of proficiency testing was conducted after visual acuity issues had been addressed at a special workbench; this workbench had a 2.25X adjustable magnifier light. I purchased the higher adjustable magnifier light to compensate for an older workforce. Ambient light at work surface was set at 60 -80 lx, with magnifier target light set at 120 lx. The inspector was given the capability to adjust ambient and target lighting to meet their personal desires. I purchased a new ESD ergonomic designed adjustable chair and allowed the inspectors to adjust the chair to their personal desires. The workbench had an adjustable foot rest under the table as well as pads at tabletop edge for the inspector to rest the forearms on while performing the inspection. The results and analysis of the proficiency testing at the special workbench are as follows:

- The eleven inspectors were tested under these conditions using only the magnifier light; they had a 98% hit and 4% false alarm rate. Inspectors reported they could see the work piece better.

- Second proficiency test, I setup a 10X microscope on a stand that allowed medial plane adjustment as well as height adjustment. This allowed the inspector to look straight into the microscope's eyepieces without hunching or bending at the neck. The eleven inspectors were tested under these conditions; they had a 100% hit and 8% false alarm rate. Four out of the eleven inspectors did not use the microscope during the proficiency test.

- A third proficiency test was conducted with 10 PCAs, each inspector was told to rework all termination defects found. At the conclusion a second inspector would check the board for termination defects. Of the eleven inspectors tested under these conditions, they had a 100% hit and 2% false alarm rate. Second inspection of the rework by the eleven inspectors had a 100% hit and 0% false alarm rate.

I conducted a workout with the group of inspectors to determine reasons for the difference between the two rounds of proficiency testing. The inspector attitude was outstanding; general consensus was they wanted a workstation similar to the test workbench. Inspectors gave credit for the improvements solely on the basis of the workstation; the workstation made the inspection task easier. The inspectors had no problem with making corrections to termination defects and general consensus was it should be part of their inspection process.

Workspace Arrangement and Environment

I decided to change the facility layout and move four workstations to the SMD area. This would allow for real-time verification of customer product. Barriers to the move were as follows:

- Defect database management would need to change; the inspector would have to enter the defect data into the database at time of inspection instead of writing the defects per product on a sheet of paper to be entered by another person at job completion. In other words, I needed to take the inspection defect reporting process paperless and real-time.

- The inspectors wrote the defects on a sheet of paper to inform rework technician what to fix. The inspection sheet tracked the defect per product as well as the rework and re-inspection to ensure conforming product after rework step. I would still need to provide for this path: inspection, rework and re-inspection but through a paperless process.

- I did not want to put a rework station and all the required tools in the SMD area; however, I did want termination defects fixed at the inspection station. All other defects, such as orientation error, missing component, component damage, etc., I wanted reworked by a rework specialist trained per IPC -7711 industry specifications. Therefore, I would need to change the work rule from it is unacceptable for the inspector to fix a termination defect to it is expected that the inspector can fix termination defects, and evaluate and approve the rework.

- Additionally, I wanted triggers to be established that at a certain defect level an e-mail would be generated and sent to the engineering staff informing this group there was a process problem with a customer product at SMD. This would provide actionable defect data and feedback to the inspectors on the quality of their respective inspection performance.

I used the proficiency testing schema to give inspectors confidence that they could rework and evaluate quality of rework for termination defects. This was seen as job enrichment to the inspectors. This did require a re-design of the inspector's workbench to support the solder iron equipment. Process has been in place since the middle of March 2008 reducing cycle time.

I formed a team, with team membership including IT and engineering staff. The team designed a system with two, 17 inch LCD flat screens in tandem for the purpose of taking the defect database to real-time and paperless. The screens would be used as follows: one screen would be used for configuration management and the other screen would be used to enter defect data, real-time, by the inspectors. Additionally, the defect database was modified to support data entry by the inspectors; send an e-mail to engineering if defect type exceeded a trigger point; and allowed for printing an inspection status sheet equivalent to what was handwritten prior to this change. By April 1, 2008 this system was in place. Moreover, engineers were receiving automated e-mails that a problem existed with a customer product at SMD.

During beta testing of the real-time, triggered event, defect database a customer product was stopped due to a solder bridge termination issue on SMD manufacturing line two. Further investigation found the exhaust blower for the reflow oven was under-rated: specification called for 1000 CFM minimum exhaust; however, blower was only rated to 600 CFM. No telling how much this cost my company over the past several years before the blower was finally replaced. Moreover, engineering is currently working on a project to put pilot tubes in the oven exhaust pipes for purpose of monitoring and ensuring adequate exhaust flow during the reflow process.

The facility's climate is temperature and humidity controlled: 70 – 74F and 30 – 34% RH. However, a comfort survey was provided to the inspection department personnel. Personnel reported their feet were cold as well as their ankles and feet swelled during the course of the day. Temperature surveys at one foot above floor and underneath inspectors' worktable showed space temperature in control. Took pictures of each inspector, how they sat in their respective chairs and placement of feet, observing foot rest was under the seat on a metal bar as well as the seat cushions were designed for one size fits all. Both conditions most likely were affecting blood circulation to the foot. I purchased a new ESD ergonomic adjustable chair along with placing an adjustable foot rest under a special workbench I used for round second proficiency testing and as a mock-up for the new inspector workstation.

Future

- Project will continue to monitor success of deliverables as measured by a reduction in termination defects as well as the associated reduction in termination type 2 error rates using a c-chart for both measurements.
- Real-time defect database system triggering levels and required response by engineering to a triggering event will be monitored for ongoing improvements. Specifically, in April 2008, I am working on improving notification method to heighten a sense of urgency as well as documentation requirements associated with actions taken and SMD process reaction to the actions taken.
- Additionally, surveys and interviews of inspectors will be conducted on a regular basis to determine the effectiveness of workstation comfort. On April 4, 2008 I held a work out with the inspectors discussing posture and eye fatigue issues. Inspectors were told to stand-up and walk around their respective workbenches every 20 minutes. To keep their arms as close to their body as possible when performing an inspection.

- The project will further expand starting April 7, 2008 to include orientation errors; this will be done through a team of managers and engineers under my direction. The team will begin the process of understanding orientation errors by defining part markings and how front-end engineering programs the CNC SMD machine.

Summary

Inspector required skills, knowledge and rules based training elements were reviewed with the following items of interest noted:

- Prior to this project no inspector skill based abilities were verified, such as attention-to-detail capability and visual acuity and color perception capability. Both are important to the quality of the inspection; the first relates to the state of attentiveness and the second relates to the quality of the eyes. All new inspectors will be required to take attention-to-detail testing as well as acuity and color perception tests as qualifiers of an inspection position.

- Prior to this project our inspectors received very little feedback related to the quality of their respective inspection capability. With the new action message system, engineers are not only checking the SMD process for instability, but providing feedback to the inspector on the cause and complexity of the defect. This type of feedback will improve inspectors rule based knowledge enhancing the quality of the inspection task.

Both of these improvements will heighten the inspector's capability.

By March 31, 2008 real time defect data with event trigger notification requiring engineers to take action was operational. Observations are being seen, which have already resulted in changes expected to result in SMD defect reduction. This new approach has revitalizes my engineers and SMD staff.

More importantly, the new workbench with the ergonomically designed chair and foot rest has put a spark in the eyes of my SMD inspectors. Other staff members have already been asking when their respective workstations will be redesigned.

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