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A Method to Investigate Printed Circuit Board Supplier Rework Processes and Best Practices

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Abstract

Several incidents occurred that prompted a team to investigate Printed Circuit Board (PCB) supplier best practices and rework procedures. Two of the more prominent incidents that occurred and precipitated the best practice and rework investigation include: 1) the stripping of cured soldermask/legend which led to weave exposure and the scrap of 100 affected PCBs, and 2) evidence of a foreign inclusion that is believed to have been a catalyst for Conductive Anodic Filament (CAF).

An investigation into the root cause of the exposed weave PCB manufacturing lot (item #1 above) determined that a caustic rework procedure was responsible for the erosion of the buttercoat leading to exposed glass fibers on the surface of the boards. Additionally, it was derived that Foreign Object Debris (FOD) played a catalytic role leading to CAF resulting in a short on a delivered Printed Circuit Assembly (PCA) (item #2 above). FOD was believed to have been created during the manufacturing process. As a result of the two events above, the team concluded it was in the programs best interest to visit each program qualified PCB supplier and conduct site surveys into the suppliers rework best practices.

The PCB suppliers site survey had three main objectives: 1) identify and document all potential rework scenarios, 2) better understand supplier FOD program and look for opportunities for improvement and 3) once all potential reworks are understood and documented, identify potential rework procedures that could be detrimental to the program and take steps to mitigate their occurrence. Through the interview of many PCB manufacturing personnel in four manufacturing locations, the PCB rework investigation team documented 60 possible rework scenarios and assessed each one's relative risk of occurring and potential impact to PCB quality and reliability using a weighted formula based on several factors.

This paper provides a structured overview of the team's methodology to investigate PCB supplier rework processes, including identifying rework procedures that have potential implications to PCB functionality, and the approach to weighting reworks to determine the associated level of risk.

Introduction

The genesis of this paper is derived from instances of defects found in PCBs that were not captured during the incoming inspection process and subsequently built into Printed Circuit Assemblies (PCAs). Ultimately these defects compromised the functionality of the system the PCAs are used in. The system consists of two subsystems, which include 1) a sophisticated electromechanical assembly and 2) a computer. Issues such as PCB defects caused by rework processes or FOD can cause degradation of the system and failure to meet specification requirements are problematic. Steps are taken to prevent these issues from occurring.

Two such instances of defects drove the team to assess the need to review PCB supplier rework procedures and best practices. The goal of the review was to determine what might lead to defects in PCBs, and to prevent, or minimize the occurrence of, these types of defects. Per IPC-7711C/7721C, rework is defined as the act of reprocessing noncomplying articles, through the use of original or equivalent processing, in a manner that assures full compliance of the article with applicable drawings or specifications.

The main focus of this paper is to provide guidelines regarding how the rework procedures were reviewed, and the system used to determine the probability of the rework causing a potential performance or functionality problem in higher levels of assembly.

Background

A series of issues with PCBs occurred, that resulted in the team's decision to look into PCB suppliers' best practices and rework procedures. Two of the more prominent incidents that took place and precipitated the best practice and rework investigation will be described in this section. Those incidents include:

1. Weave exposure found in PCBs (Goldman, et al., 2018)
2. Conductive Anodic Filament (CAF) resulting in a short on a PCA (Goldman, Grubbs, & Arthur, 2016)

Weave exposure is when there are openings in the resin of the surface layer of the PCB that expose glass fiber bundles. Weave exposure is acceptable under MIL-PRF-31032/1 provided that: 1) exposed or disrupted reinforcement fibers on the horizontal surface of the PCB do not bridge conductors, and 2) the minimum conductor spacing is not violated due to the condition. In IPC-6012, weave exposure is acceptable for Class 1 & 2, but is not allowed for Class 3.

In the instance of weave exposure that the team was reviewing, the concern was raised that the exposed weave condition could potentially reduce the minimum electrical spacing between conductors (especially tightly pitched component leads). Typically for this board design, the minimum conductor clearance is 127µm (0.005 in.). Several unassembled PCBs were provided for evaluation. During the initial visual inspection using standard magnification, it was unclear if the weave condition was weave texture or weave exposure. As a result, higher magnification was needed to accurately identify the condition. Very high magnification (200X and 400X) was used to view the weave exposure, and it was determined that the weave exposure condition was in violation of minimum conductor spacing requirements. See Figures 1 and 2 for examples of the exposed we've seen.

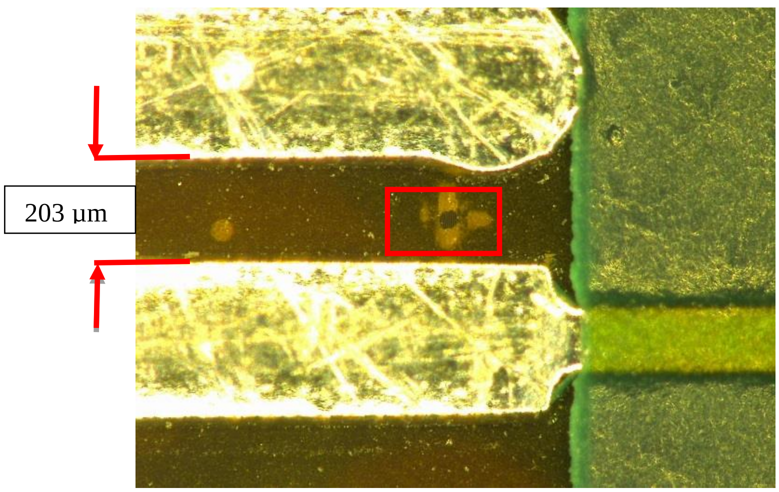

Figure 1: Exposed weave between connector lead pads.

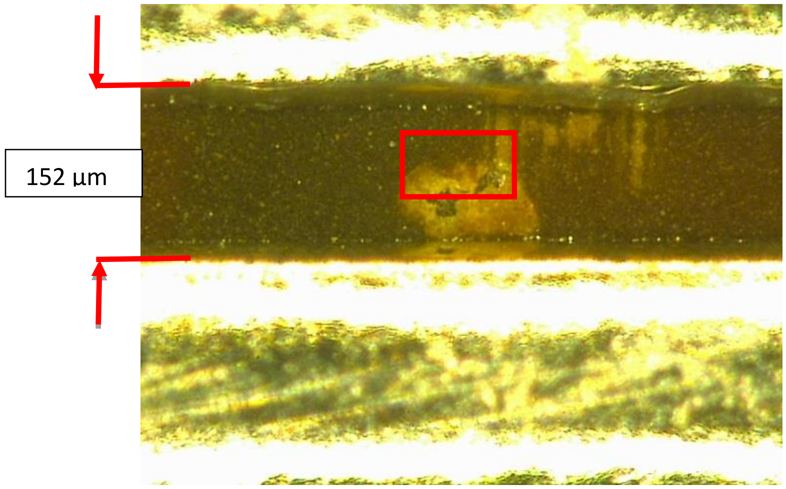

Figure 2: Exposed weave between component lead pads.

The investigation into the root cause of exposed weave, including a thorough review of the manufacturing process traveler and accompanying documentation, for the manufacturing lot in question led to the following information (Goldman, et al., 2018). The boards were reworked by stripping cured soldermask (and cured epoxy ink marking) in accordance with an in-house approved procedure which specified using a caustic stripper and then using a pumice scrubber as part of the wash down procedure. This process was conducted while the boards were full up panels. With a high level of confidence, it is believed that the result of this process which attacked the resin on top of the glass fibers, resulting in weave texture and weave exposure. The chemical stripper employed was an aggressively caustic solution using dipropylene glycol monomethyl ether as a water-soluble solvent.

The cured soldermask strip rework process resulting in boards having weave exposure is an example of an unusual supplier rework that led to the need to scrap affected PCBs. This is the first item that led the team to take a close look at supplier rework processes and best practices.

The second item that contributed to the need to review rework processes and best practices at PCB suppliers was a system failure investigation. The root cause was determined to be FOD which promoted a CAF failure. There was no direct evidence of CAF due to the PCB destruction in the vicinity of the failure site. However, there is circumstantial evidence based on FOD discovered in an adjacent location in the PWB in proximity of the burnt failure site. The PCBs are built up into a complex system, and defects at the PCB level can result in system failures. This investigation started at the PCA level and resulted in a detailed destructive physical analysis of the PCB. Some examples of relevant FOD can be seen in Figures 3 and 4.

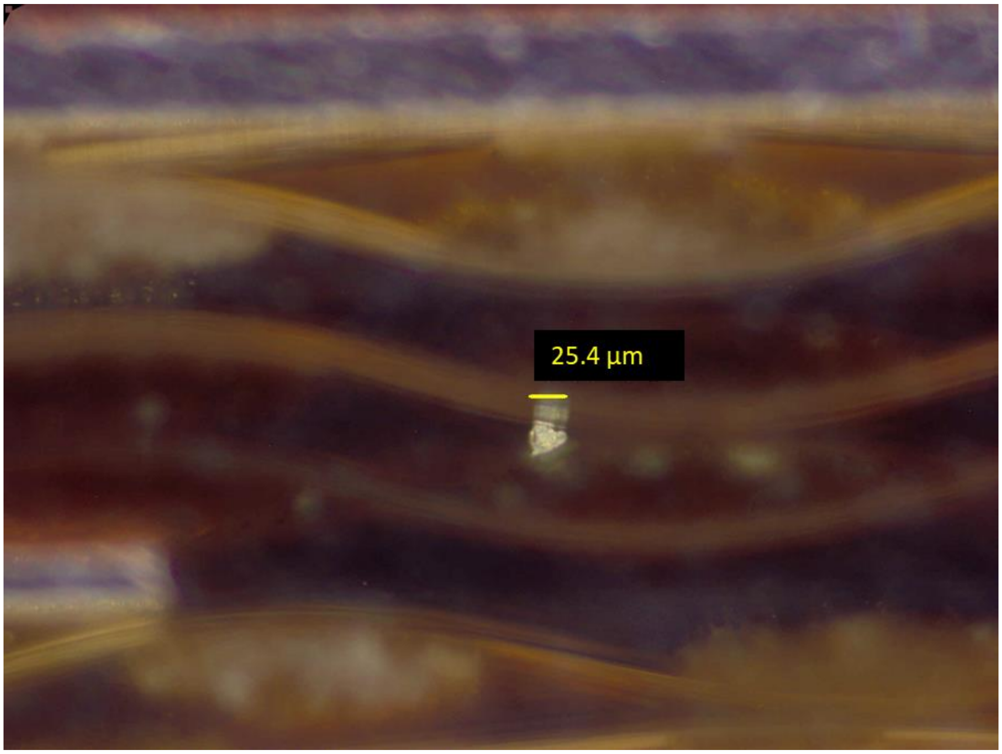

Figure 3: Example of Metallic FOD, seen at magnification of 125X in Dark Field inspection.

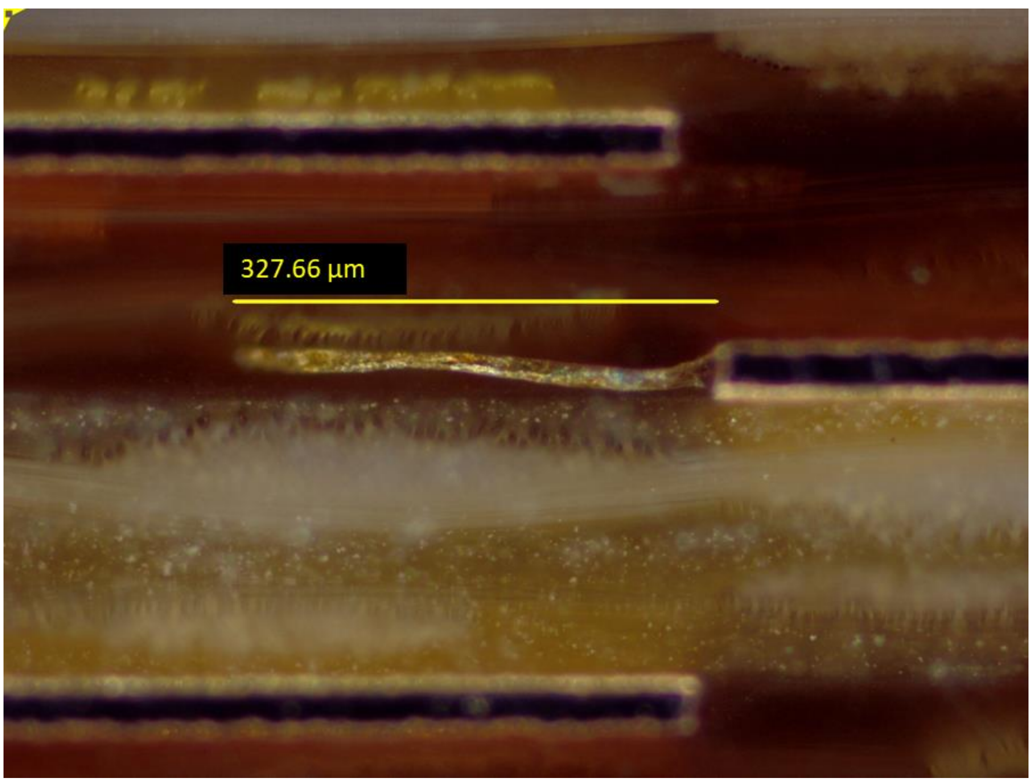

Figure 4: Example of Non-Metallic FOD, seen at magnification of 125X in Dark Field inspection

The failure mechanism of the PCA was determined to be a defect in the PCB. This conclusion was based on a number of investigation steps, including but not limited to the sectioning of three microsection coupons removed from the failed PCA, and the findings discovered during the re-inspection of the PCB conformance coupons, as well as the other panel conformance coupons within the same manufacturing lot. As a result of the failure analysis, evidence led the team to the conclusion that the mechanism causing the failure of the system was a foreign inclusion, which acted as a catalyst in propagating a crack, thereby providing a pathway for copper plating and plating residue to travel up the crack. This condition reduced the design clearance distance between a buried via (which is signal GND) and layer 11 plane (which is a 3.3V plane). This reduced distance had been breached by a conductive filament growth facilitated by plating residues over time.

Once the short was established, the heat generated by the short caused burning and melting of the dielectric material, creating carbonization (electrically conductive), which further propagated the short. The electrical short measured in the failure site coupon mount was the result of the carbonized material in the PCB (Goldman, Grubbs, & Arthur, 2016). A photo of one of the lot conformance coupons with a foreign inclusion can be seen below, in Figure 5.

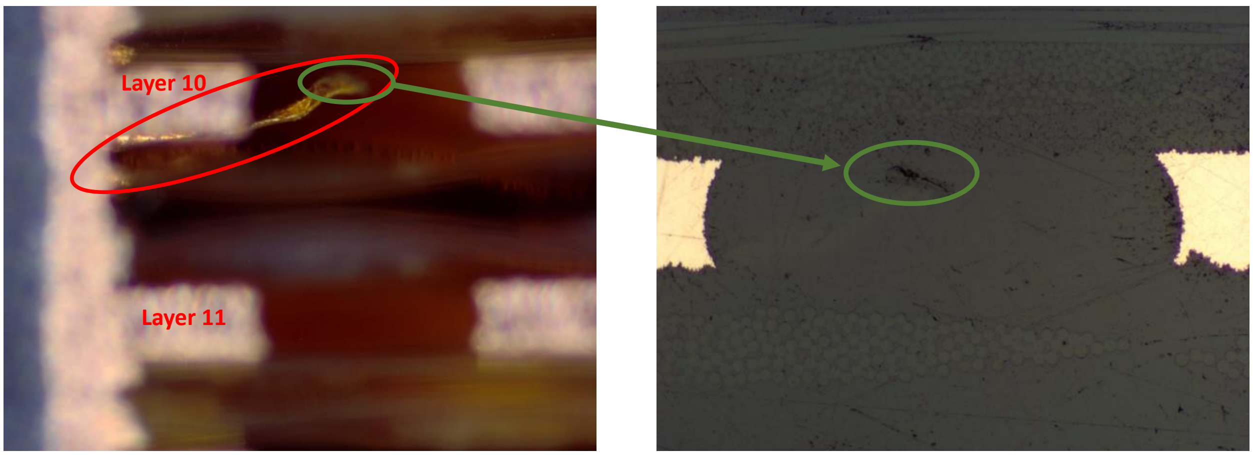

Figure 5: PCB Acceptance Coupon with FOD (Dark Field on Left, Bright Field on Right.

Approach

These two instances in combination led the PCB team to conclude it was in the program's best interest to visit each PWB qualified supplier and conduct a site survey to review each suppliers rework opportunities with the intent of identifying those rework procedures that could affect PCB quality or reliability. In addition, review supplier best practices including FOD control programs implemented at each manufacturing facility.

Over the course of a year, the design agent and procuring agent for the PCBs and PCAs visited each of the qualified PCB suppliers to conduct a best practice and rework investigation at each manufacturing process step. The PCB supplier site survey had several primary objectives. The initial focus was rework procedures occurring at the facilities. Identification and documentation of all potential rework scenarios was required so the team could eventually analyze each possible rework operation. Both high and low frequency of possible rework procedures were categorized. Low frequency procedures (occurring 2 or 3 times a year, or less) were especially interesting since they tended to be of a higher risk but could have potential impact to the team's product when they are enacted. Common (or higher frequency) rework scenarios would have been more likely to have already been identified if detrimental to the end product. Once all potential rework scenarios were understood and documented, the team worked to identify rework procedures that were determined to be most detrimental to the product based on a weighting algorithm, so that steps could be taken to mitigate their occurrence.

Another primary objective of the supplier site surveys was to better understand the supplier's Foreign Object Debris Control Plan and look for opportunities for improvement. As noted in IPC-WP-116 ("Guidance for the Development and Implementation of a Foreign Object Debris (FOD) Control Plan"), implementing and maintaining an effective FOD control plan is critical in reducing the causes and effects of FOD on hardware. Additionally, as mentioned above, FOD is believed to have been the catalyst in a short causing a system failure with program hardware (Goldman, Grubbs, & Arthur, 2016).

All suppliers worked with the investigation team in an open and honest manner in an effort to provide the most meaningful results. Through the interview of dozens of PCB manufacturing personnel at various locations, the PCB rework investigation team reviewed and documented 60 possible rework scenarios.

After completion of the site visits, one of the PCB suppliers ("Supplier A") shared an interest in collaborating with the team and played an active role in rework identification and impact analysis. The team worked with Supplier A and met a number of times either via conference calls or on-site meetings to generate a matrix documenting all potential reworks and associated attributes. When relevant, non-proprietary knowledge gathered from the visits with the other suppliers was integrated into the matrix documenting the different rework procedures done at each facility.

The goal of this matrix was to identify and categorize potential rework risks by including items that were important to both the PCB supplier and the customer, and come to a compromise regarding what the approach to different rework scenarios should look like to benefit both parties.

The different attributes that were identified as important, and subsequently included in the matrix, included the following (see Table 2 for examples):

- An identifying item number for each matrix line –used to count how many rework items there were, and have a number associated with each type of rework. There were 60 types of potential reworks identified in total.
- Department – shows at what point in the process the rework could occur. Some examples are Drill, Plating, Quality, and Reflow.
- Area – the physical location at the facility that the rework might take place at. Examples of this item are Surface Prep, Etch, Soldermask and Reflow. This item correlates to the process and department.
- Rework item – this is the name or title of the rework process
- Questions/Comments – anything the team wanted to ask or address with the supplier during this review. This included items like: is this rework type applicable to our product?
- How the rework was performed – a brief statement regarding what steps took place during the specific rework
- How the instructions for rework are generated and documented – the method of flowing the rework instructions to the person performing the work. An example is that a rework sheet is written by the process engineer.
- Where the rework is logged – the location where records and results of rework are kept.
- The associated risk – results from the rework process that could negatively impact product
- How inspected – how the areas reworked are inspected after rework completion. Examples of inspection types are Visual, Scope, and Micro section
- Rework frequency –See Table 1.
- The ability to detect issues - See Table 1.
- The chance of rework success - See Table 1.
- Severity of impact to our product - See Table 1.
- Weighted risk of the rework – combination of the four items weighted, per Table 1, to determine the risk the rework poses to PCBs
- The team's recommendation regarding the use of the rework
-

The items below were identified as the primary weighting categories to be used in the algorithm that determined the consumers (customer) risk level, identified in our matrix as "weighted risk" associated with each of the 60 identified reworks.

- Rework frequency
- The ability to detect issues
- The chance of rework success
- Severity of impact to our product

These columns were used to compose the weighted formula for the risk determination and were viewed as a method to weigh important factors from both the customer's and manufacturer's perspective. A breakdown of how each item was scored to determine the final risk is shown in Table 1. Each item was given different levels of severity, which was assigned to a numerical value. The lower the numerical value, the lower the associated risk. These numerical values were determined by the PCB subject matter experts. For example, in Table 1 it's shown that if the rework frequency is daily, that item is given a 1, because the risk associated with daily reworks is considered lower than the risk associated with a rework that is hardly ever performed. Reworks with a frequency of hardly ever performed were given a numerical value of 10, to signify a higher risk to product. Common reworks are less of a risk because they're well known and documented, and performed frequently, thus more practiced and typically recognized as having limited risk.

Table 1: Matrix categories and scoring used to determine weighted risk of rework

		Numerical Scoring				
		1	**3**	**5**	**7**	**10**
Matrix Item	**Rework frequency**	Daily	Weekly	Monthly	Yearly	Hardly ever
	Ability to detect issues	Never miss	Unlikely to miss	May have escapes	Hard to find	Risk of escapes
	Chance of rework success	Always	Good chance	50%	Maybe	Not hopeful
	Severity of impact to our product	low	-	moderate	-	high

The rows in Table 1 list the different items that were used to calculate the risk. The weighted risk is derived from a formula comprised of the numerical scoring of these items and a multiplication factor.
Weighted risk = (rework frequency x 1) x (ability to detect issues x 3) x (chance of rework success x 2) x (severity of impact to product x 3)

The lower the multiplication factor, the less concerned the team was with that item. The options for the factor are 1 (low concern), 2 (moderate concern), or 3 (high concern). This was agreed upon by the prime contractor and the supplier. The multiplication factor for each option remains constant in the formula. For example, severity of impact is always assigned a multiplication factor of 3 (to calculate the risk for any type of rework). This is because the team determined that severity of impact to the product plays a larger role and possesses a higher risk than the other items, so it's assigned a higher multiplication factor. The chance of rework success was always multiplied by a factor of 2 in the formula, because instances may occur where a rework is thought to be successful, but it may not have been detectable or verifiable so there is a chance that the rework was not actually successful. The rework frequency was multiplied by a factor of 1, because it was determined that a low concern was associated with this item.

Table 2: Examples of line items from the matrix including the key attributes and weighted risk calculation

Item	**Department**	**Area**	**Rework item**	**How was the rework performed?**	**Associated Risk**	**How is it inspected?**	**Rework Frequency**	**Ability to Detect**	**Chance of Success**	**Severity of Impact**	**Weighted Risk**	**Recommendation**
1	Reflow	Reflow	Unflowed Tin Lead	Re-Reflow	Thermal	visually	10	3	1	10	5400	OK to process
2	Inner layer Image	IL Coat	wrinkles	Wash down - If exposed develop and strip if not then develop then rerun through surface prep at wash down speed to minimize etch loss	foil reduction up to 25 u"	established process final microsection	1	3	3	5	810	OK to process

3	Screening	Soldermask	Soldermask stripping	run through SM developer if not cured	Attack buttercoat, weave exposure	visual	10	10	7	10	126000	do not use without approval
4	Drill	Mechanical Drill	undersized holes	re-drill	miss-drill	visual/ microsection	7	5	3	10	18900	do not use without approval

For reference, the values assigned to each category seen in Table 1 and Table 2 were based on team consensus, and, while generally consistent between study participants, there were some conflicting opinions which were averaged to give the most representative assigned value. Items 1 and 2 in Table 2 (unflowed tin lead and wrinkles) provide examples of rework processes the team determined were low risk and ok for the supplier to proceed with in the future. As previously mentioned, the team used the information in the first few columns to assign a numerical value to the items listed in Table 1 (also shown in Table 2 with numerical value assigned). The weighted risk column was then calculated based on the formula described above.

Items 3 and 4 in Table 2 are examples of rework procedures that have a high weighted risk associated with them, and therefore the supplier is not allowed to use these reworks without customer approval.

Item 3, cured soldermask stripping, requires an acidic bath as part of this rework. This rework was given a 10 for the rework frequency, because the supplier could not remember the last time they used this process. The ability to detect issues after rework item 3 was a 10, because any issues might not be detectable under standard visual inspection conditions, or it could be misinterpreted under standard inspection conditions. The chance of success was given a 7 for this item, because success is dependent upon a few things, including but not limited to: length of rework and how aggressive the mechanical scrubbing process is. The severity of impact was 10 because any chemicals remaining could be trapped in the laminate during the assembly processes, and then when it's introduced to a high humidity environment and a voltage differential, there's a high potential for CAF growth. These numbers were used in the formula to weight the risk, and a total value of 126000 was calculated for cured soldermask stripping. The team used this information to determine that soldermask stripping rework is a high risk to our product.

The rework for item 4, undersized holes, consists of re-drilling the holes to the required size. There is a low likelihood that the drill bit will perfectly fit back into the previously drilled hole. There are several risks associated with the rework process including registration issues, sidewall damage, and drill chattering. These risks can cause the copper barrel wall to be deformed and ultimately unacceptable to product specification requirements. This rework is inspected visually, post-rework. The rework frequency was assigned a 7 (yearly). The ability to detect issues post-rework was given a 5, because the hole is visible but it's hard to see into it perfectly in which can lead to inspection escapes. The severity of impact was given a 10 because of the issues that this rework can cause, and if there is an escape, it can severely impact the end product. These numbers were used in the formula to weight the risk, and a total value of 18900 was calculated for mechanical drilling of undersized holes. The team used this information to determine that mechanical drilling of undersized holes rework is a high risk to our product.

Risk Mitigation

After compiling all the rework scenarios and associating a weighted risk with each, the team populated the decision matrix and determined a path forward to minimize the potential of rework occurring that would negatively impact our PCBs.

As a result of the investigation into supplier rework processes and best practices, based on the results of the rework matrix the team modified our program PCB specification documentation to identify and limit risky rework processes which could have a potential impact to product quality or reliability.

Conclusion

A methodical approach was used to assess PCB manufacturers rework operations. After thorough investigations at each manufacturing location, the team worked with one supplier to develop a matrix of all potential rework scenarios. The matrix used four weighted elements to determine the level of risk associated with each rework process. The matrix was then used to identify the rework processes that the team deemed most problematic and had the potential to negatively impact PCB quality and reliability. Once the investigation was complete and the rework matrix finalized, all undesired rework processes identified during the investigation were incorporated into program documentation as restricted rework processes with the intent of reducing future system failures and improving overall PCA quality.

References

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