Get Rid of the Wooden Pick and Other Neanderthal Approaches for Rework of Underfilled Components

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Abstract
Multiple Electronics Markets are driving the growing need for components with higher performance in smaller form factors with higher pin count and greater reliability.

Ball Grid Array's (BGA's) and Chip Scale Packages (CSP's) are two of the most widely used components for higher pin count applications, however the addition of underfill is required to provide the level of reliability that is needed when these components are subjected to high thermal and mechanical stresses.

One downside of underfilling BGA's and CSP's is that it makes the rework process extremely difficult or impossible based on the underfill composition that is used. Current underfilled rework practices include Neanderthal terms such as a wooden pick, small chisel, exacto knife, prying, twisting or shearing the component to separate it from the underfill bond and scraping the underfill off the site. These manual rework methods lack the Process Control that is inherent in the initial board assembly process making rework the weak link for these high reliability applications.

This paper describes an alternate process for reworking underfilled components that provides machine-based Process Control and eliminates the non-repeatable, manual processes that are currently in use.

Introduction
Some examples of products driving the need for higher performance devices in smaller form factors with high reliability include smart phones, smart watches and tablets in the Consumer Electronics Market; engine control systems, cameras and image sensors in the Automotive Market and drones, satellites, man packs and global positioning systems in the Military and Aerospace markets. These products continue to use smaller and smaller devices to improve portability and reduce space. Fine pitch BGA's/CSP's are typically the components of choice however the smaller solder spheres make these high pin count devices less reliable when subjected to harsh environmental forces.

Underfill has been a long-term solution at the package level, protecting flip chip from the Coefficient of Thermal Expansion (CTE) mismatch between the die and the component substrate.

The primary solution for increasing the reliability of BGA's/CSP's is to apply underfill to the space between the bottom of the component and the top side of the board.

Underfill
Underfill is typically an epoxy-based polymer that is dispensed underneath one or multiple sides of a BGA or CSP. Underfilling components can be performed at room temperature but preheating the board to as high as 70˚C increases the flow rate under the component through capillary action. The cure time varies from five minutes to one hour depending on the underfill that is used and the curing temperature which ranges from 100-150˚C [1].

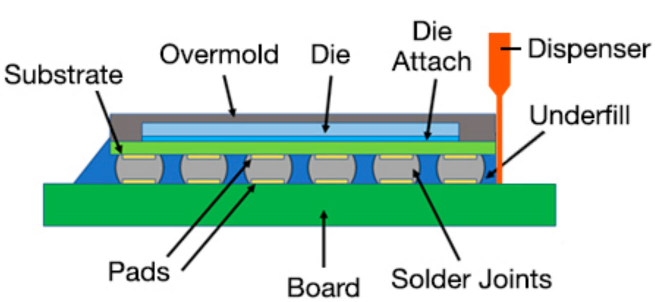

Figure 1 – Underfill (in blue) Dispensed Between the Bottom of the BGA/CSP and the Top of the Board [2].

The use of underfill is becoming increasingly popular because it provides a strong mechanical bond between the BGA/CSP and the board. Underfill provides excellent protection for the solder joints against thermal and mechanical strain such as those experienced during thermal shocks, drops and vibrations.

The solder joints of non-underfilled BGA's/CSP's can be damaged by harsh environmental forces however the addition of underfill can strengthen the solder connections by a factor of 10 [3].

Underfill also decreases the stress caused by the Coefficient of Thermal Expansion (CTE) mismatch between the BGA/CSP and the board by redistributing the stress from just the bottom of the solder spheres to the entire component.

The iNEMI 2019 Board Assembly Roadmap (Rework Section) states that one of the most significant rework challenges now and for the future is reworking underfilled area array devices especially those with minimal/zero adjacent clearance [4]. To further complicate things, some underfills are categorized as non-reworkable due to their excellent stability at temperatures well above the melting point of lead-free solder. Thermal-based rework processes or current thermal/mechanical rework processes cannot remove a BGA/CSP with non-reworkable underfill. There has also been some work involving the use of chemical solvents to remove underfill, however there is resistance to adding solvents to a high reliability device and concern about potential damage to adjacent components. In addition, the process of breaking down underfill with a chemical solvent is slow [5].

Just like non-reworkable underfills, reworkable underfills must also be heated to high temperatures above the melting point of lead-free solder to soften the underfill enough to allow the BGA/CSP to be removed. Current rework processes for removing underfilled BGA's/CSP's include Neanderthal terms such as a wooden pick, exacto knife, small chisel, twisting, prying and scraping off the underfill on the site. One recommendation for reworking underfilled components is not to guarantee yield rates due to the high potential for damage.

The objective of underfilling BGA's/CSP's is to provide high reliability products typically in small form factors that can withstand thermal and mechanical shock in harsh environments. If we look at current BGA/CSP rework processes without underfill, we can find a wide range of off-the-shelf rework equipment that includes a high level of automation, closed loop thermal control and total process control or close to it. However, most of these great features go out the window when underfill is added to the rework equation as the process become fully or largely manual because underfilled BGA's/CSP's cannot be thermally removed like non-underfilled components can.

Overview of Current Underfilled Rework Processes (Reworkable Underfill only)

Some investigation of the underfill that is used for a specific application is done to determine if the underfill is reworkable or non-reworkable, however trial and error is the true test as some underfills that are categorized as reworkable do not soften enough when heated to allow the component to be removed [6]. A hot air gun or a hot air nozzle is used to heat the component beyond the melting point of lead-free solder to soften the underfill enough so that the component can be manually pried or twisted off. During the component heating process, the underfill around the component is typically scored with tweezers or a knife to make the component removal process easier and to minimize the number of adjacent underfilled discrete components that come off along with the underfilled BGA/CSP.

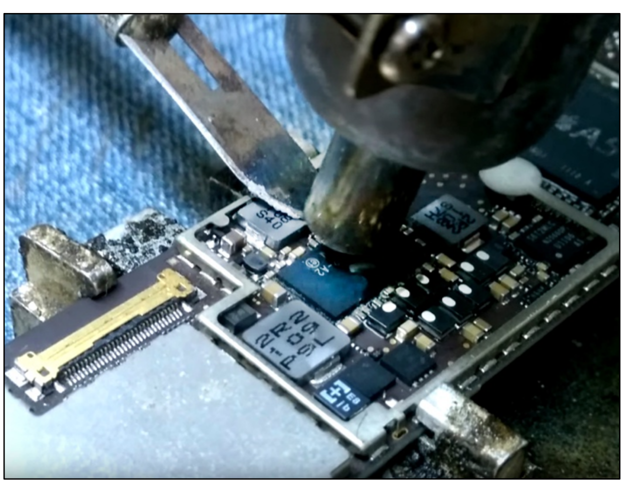

Figure 2 - Underfilled BGA During Manual Heating Process [7].

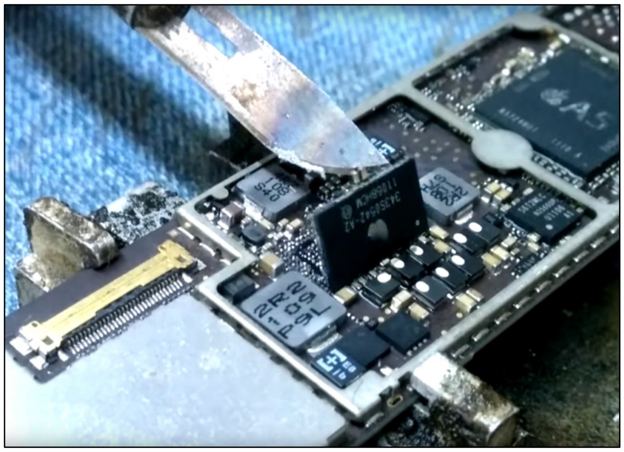

Figure 3 - Underfilled Component that has been Pried off with Exacto Knife after Heating [8].

The majority of the underfill typically remains on the site making the site cleaning process extremely difficult. The site is heated a second time to assist with the delicate task of scraping the underfill off the site.

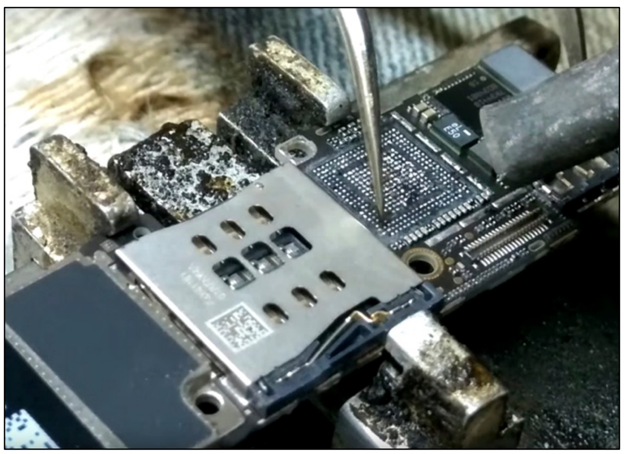

Figure 4 - Second Heating Cycle to Assist with Scraping off the Underfill Remaining on the Site [9].

One alternative method to scraping off the underfill is to use a hand-held Dremel tool with a flat end horsehair brush which has proven to be successful for some applications [10]. The final step is to use a soldering iron and solder wick to prepare the pads and the site for the component reattachment process.

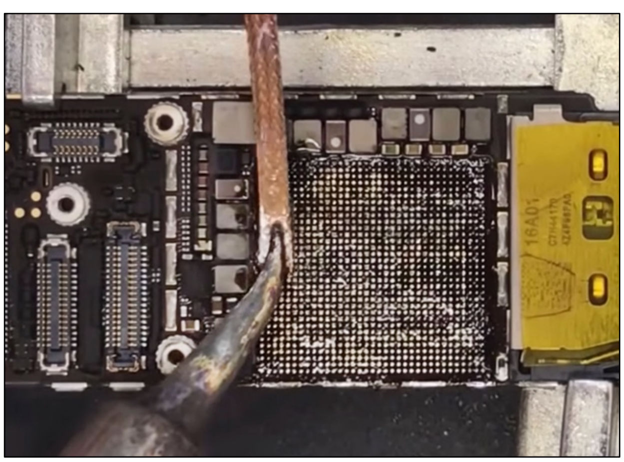

Figure 5 - Third Heating Cycle using Solder Wick and a Soldering Iron to Prepare the Site for Component Replacement [11].

One significant improvement that has been made in the underfilled rework process involves the use of a hot air nozzle with a mechanical "finger". After the underfilled BGA/CSP has been heated, the mechanical "finger" is manually or automatically engaged to remove the component.

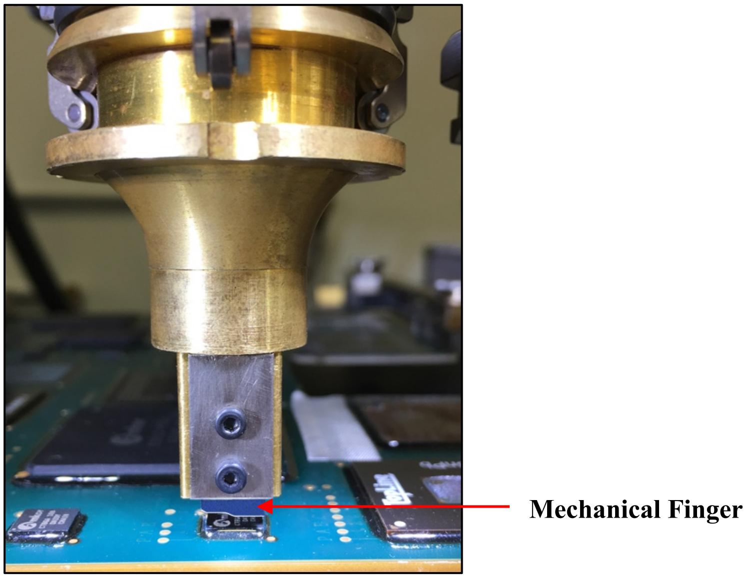

Figure 6 - "Finger" Nozzle [12]

However, many underfilled components have little or zero adjacent clearance on all four sides which prevents the "finger" from engaging the component.

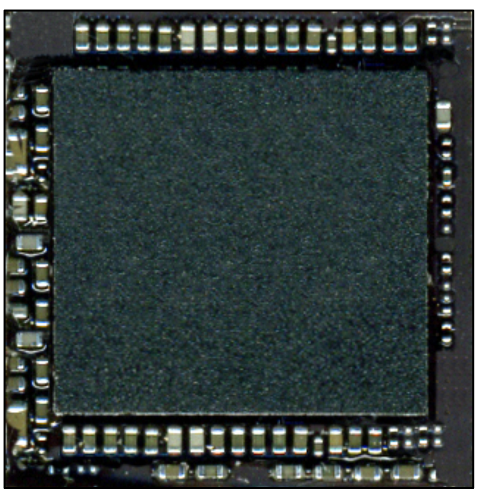

Figure 7 - Underfilled CSP with Zero Adjacent Clearance.

There are several potential issues with current underfill rework processes. First, multiple heating cycles are required and all or most of these processes are manually controlled by the operator. In addition, the heating cycles must be done at high temperatures that exceed the melt point of lead-free solder to soften the reworkable underfill. Portable consumer electronics can have multiple underfilled components side-by-side with zero adjacent spacing. Extreme care must be taken to not overheat the adjacent underfilled component as the solder will seep through the underfill causing the adjacent component to fail. Second, manually prying or twisting the underfilled component to remove it can result in site damage if the underfill is not completely softened everywhere underneath and around the component. Non-underfilled BGA's/CSP's are typically removed with vacuum after heating. If the component is not fully reflowed, the vacuum is not strong enough to remove the component thereby protecting the site from damage. However, the process for removing underfilled components is more subjective as the underfill never reaches a liquid state so there is always some resistance when the operator performs the prying or twisting action. Third, carefully scraping off the underfill remaining on the site does not seem to be a process that should be associated with the rework of high reliability devices especially fine pitch devices in small form factors as the small pads and solder mask can be easily damaged. In addition, the majority of the underfill remains on the site after the component has been removed making the site cleaning process extremely difficult. The use of a hand-held Dremel tool appears to be an improvement but certainly not the ideal approach. Fourth, metal-to-metal contact using solder wick and a soldering iron to prepare the site for a replacement component also carries the risk of damaging the pads and solder mask.

New Approach for Reworking Underfilled BGA's/CSP'S

A new approach for reworking underfilled components involves a high precision milling machine designed specifically for milling electronic components. This new approach has been in development for over eighteen months.

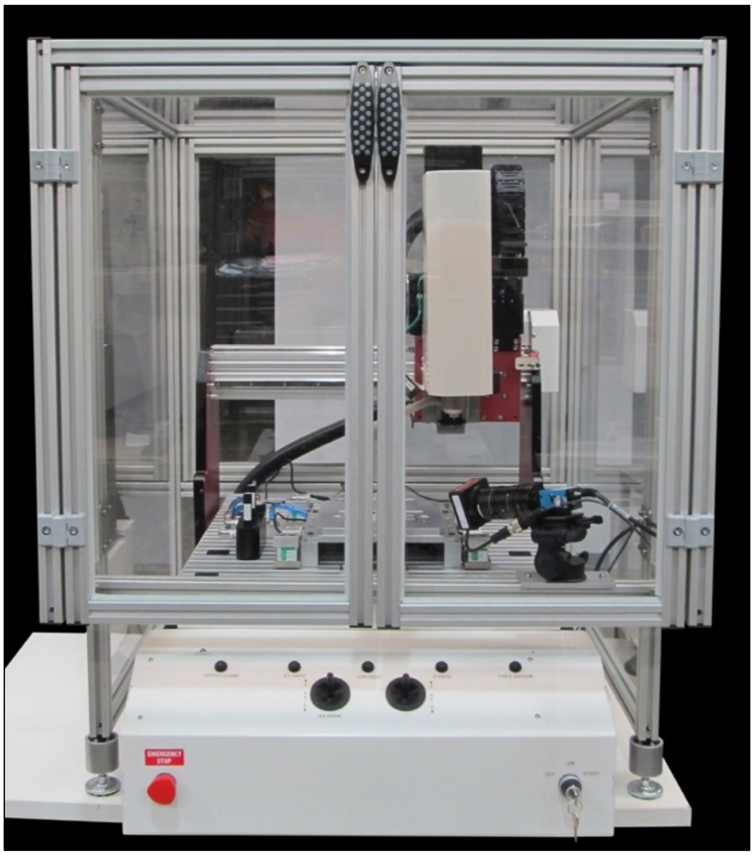

Figure 8 - High Precision Milling Machine for Electronic Components.

CNC-based milling of underfilled BGA's/CSP's has already been implemented by some companies with good or promising results however the machining centers are sometimes off site at a machining contractor where standard electronic manufacturing practices are not otherwise in use. Even if the machining center is on site, CNC programming language is used, and an expert machinist is required. The CNC machine is also in a remote area away from the rework area due to its large footprint and the use of lubricants.

A new high precision milling machine for electronic components addresses all of these CNC-based milling issues. Custom software that is structured like rework machine software instead of CNC programming language allows the milling processes to be developed by a Process Engineer and run by a rework operator. The entire underfilled BGA/CSP rework process can be self-contained in the rework area(s) in the factory in the same way as non-underfilled rework processes are currently done due to its small footprint, lack of lubricants, ESD enclosure, and a proprietary vacuum capture system.

One critical requirement is that the software must be easy to use. The new milling machine software is structured like BGA rework machine software but is easier to use as no thermal profiling or thermal cycling is required. The milling pattern generator automatically creates the milling pattern based on the component "X" and "Y" dimensions that are entered.

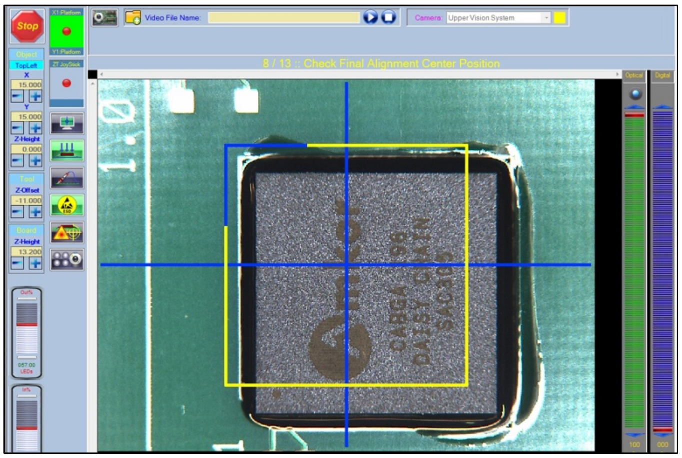

Figure 9 - Milling Pattern Generated from Component X and Y Dimensions.

A camera system and joysticks are used to quickly and easily position the milling pattern over the component to be milled.

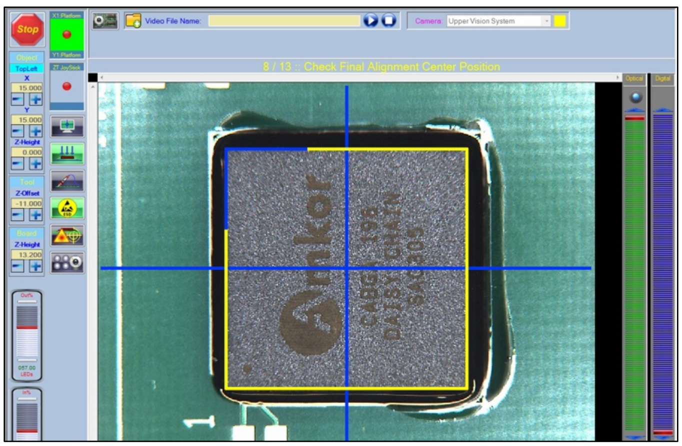

Figure 10 - Milling Pattern Positioned over the Component to be Milled.

Irregular shaped patterns for components such as RF shields can also be easily generated using the line segment pattern generator that allows the outline of the component to be traced. All milling patterns that are created are stored in the pattern library for use on future applications

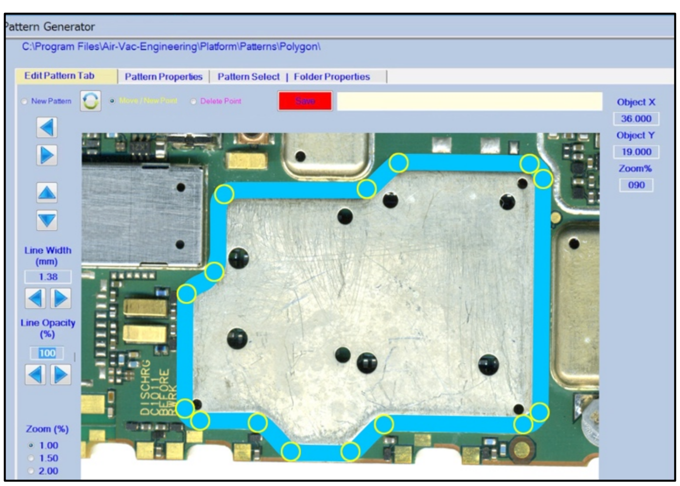

Figure 11 – Milling Pattern Generated for RF shield.

There are several other critical requirements for high precision milling to be effective. First and foremost is flatness and coplanarity. Vacuum-based or mechanical-based board holding and support is used and may be application-specific as any flexing or movement of the board during the milling process guarantees failure. In addition, the milling head and end mil must be perfectly coplanar to the component to be milled.

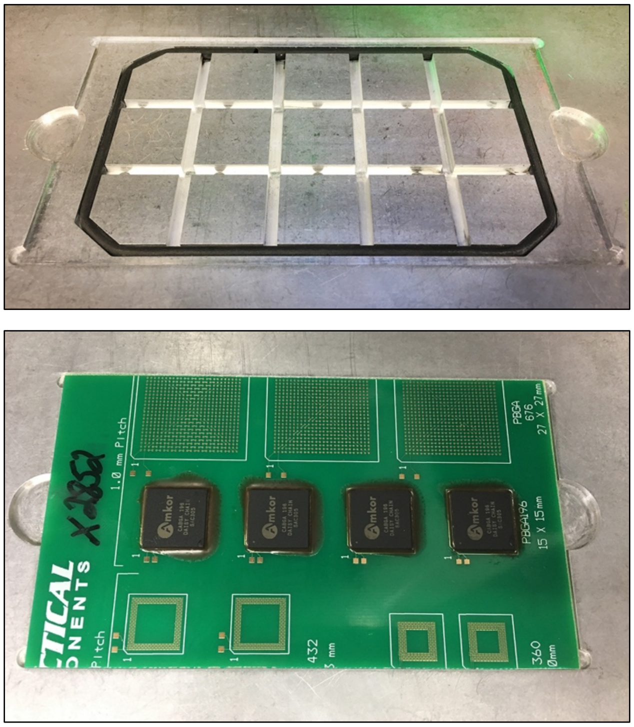

Figure 12 - Vacuum Hold Down of Board.

Another critical requirement is extremely accurate measurement of the board height and the component height. Operator-based measurement with digital calipers does not provide the level of accuracy required for high precision milling. A laser with an automatic multi-point measuring routine is used to precisely measure the board and component heights.

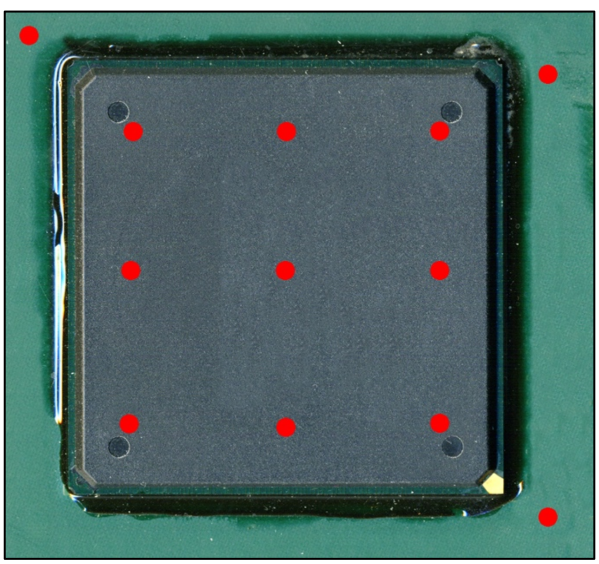

Figure 13 - Automatic Multi-Point Laser Measurement of Board & Component Heights Prior to Milling (Illustration).

The laser measurement data automatically determines the optimal number of milling cycles and the depth of each cut. The initial cut removes all or most of the component body while the finishing cut smooths out any irregularities from the initial cut(s) so their depths are typically significantly different.

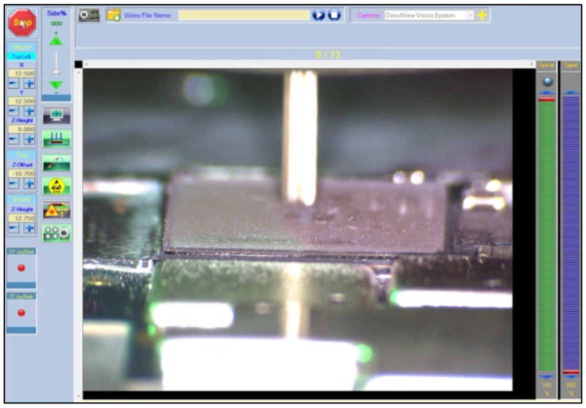

Figure 14 - Underfilled BGA After Initial Milling Cut.

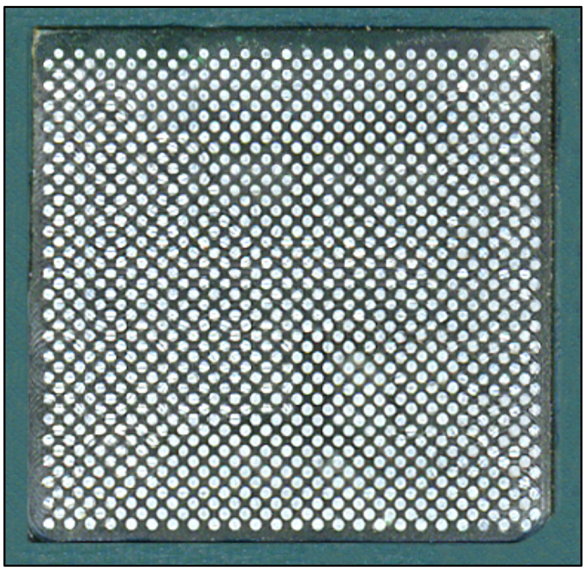

Figure 15 - BGA Site After Final Milling Cut.

The high precision milling machine provides the capability to make a controlled depth of cut as shallow as one thousandth of an inch. Different size end mils may be required for the initial cut and the finishing cut depending on the overall component height. The automatic tool changer handles this task including the precise measurement of the end mil length after the tool is changed.

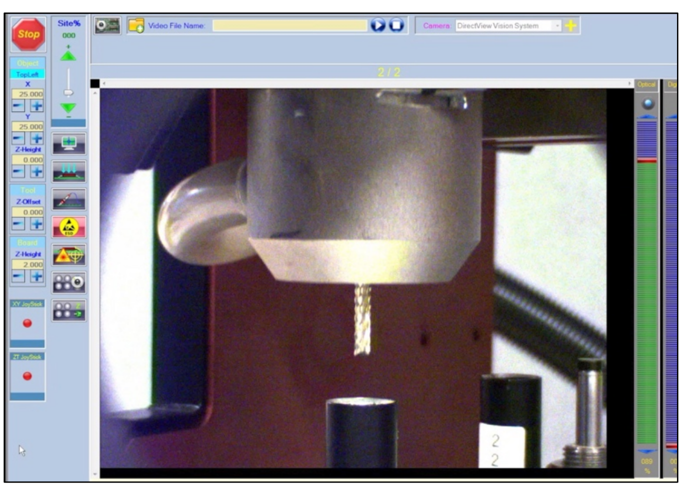

Figure 16 - Tool Changer

An ionizing system neutralizes static electricity inside the safety enclosure by flooding the area with positive and negative ions. A color-coded light identifies when the milling area is static-free and ready for milling.

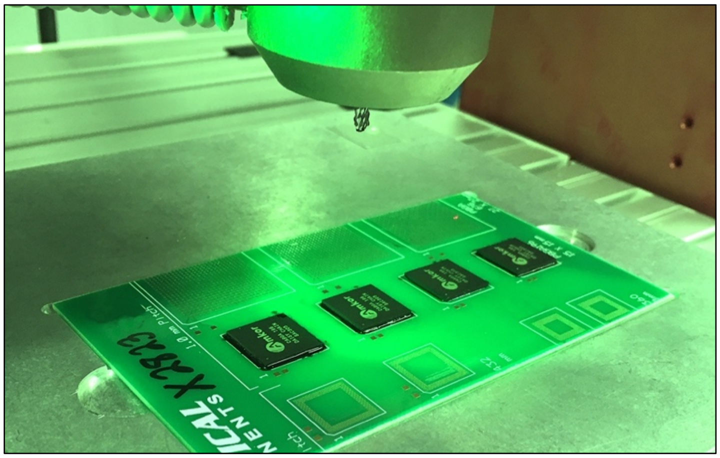

Figure 17 - Ionizer System

A proprietary vacuum removal system effectively removes particulates during the milling process. No heating cycles are required to mil the underfilled component and both reworkable and non-reworkable underfill can be milled.

Milling Study (Phase 1)

Twelve 15mm BGA's with 1.0mm pitch were soldered onto three test boards using a BGA rework machine with the exact same thermal profile. This component was selected due to its relatively high standoff from the board after soldering as it allows a large volume of underfill to be applied creating a worst-case scenario for milling. All twelve BGA's passed continuity testing after the initial soldering process. Board #1 was the Baseline Board where no underfill was applied to BGA's #1-4. Zymet X2823-B reworkable underfill was applied to BGA's #5-8 on Board #2 and cured for four minutes at 140˚C. Zymet X2852c non-reworkable underfill was applied to BGA's #9-12 on Board #3 and cured at 150˚C for 5 minutes [13].

The four BGA's without underfill on the Baseline Board were removed, site cleaned (using vacuum-based, non-contact solder removal system) and replaced on a BGA rework machine.

The eight underfilled BGA's on Boards 2 and 3 were milled on a high precision milling machine designed specifically for electronic components. The milling pattern was generated automatically by entering the 15mm "X" and "Y" component dimensions. The Board Image function was used to teach and save the four milling locations on the board.

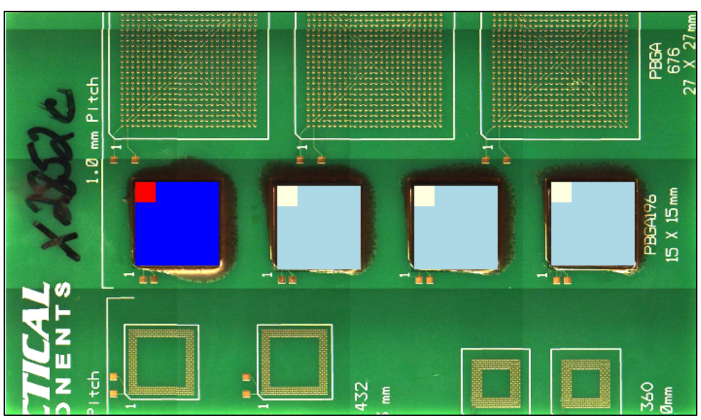

Figure 18 - Board Image of the Four Milling Locations.

Each test board was held in a vacuum fixture to prevent movement and flexing during the milling process. A high precision laser automatically measured multiple points on both the BGA and the board to accurately calculate their heights. This data was used to automatically create an optimized milling process including the number of milling passes and the depth of each cut.

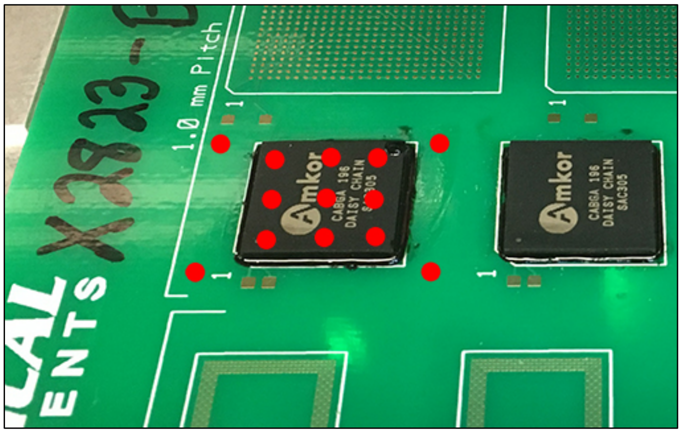

Figure 19 - Test Board Held in a Vacuum Fixture. Multi-Point Laser Measurement Accurately Measures the BGA and Board Heights (Illustration).

The laser measurement system was also used to measure the height of the underfill and solder that remained on the site after the finishing cut for the eight underfilled devices with the average height being 0.13mm (.0005 inches). No site cleaning or touch up of the 196 pads on the eight underfilled BGA's was performed prior to the component re-attachment process.

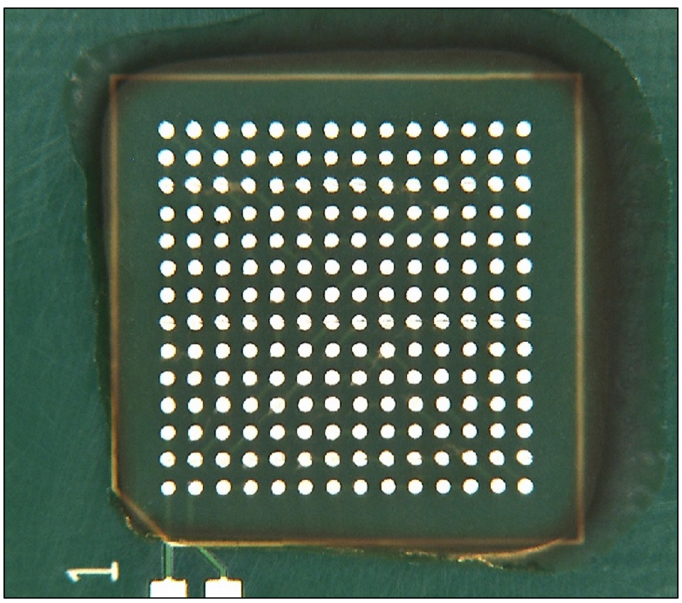

Figure 20 - Close-Up of Underfilled BGA Site After Milling.

Eight replacement BGA's were soldered onto the underfilled sites that were milled using the same BGA rework machine and thermal profile that soldered the original components onto the three test boards.

All twelve replacement BGA's passed continuity testing. The three test boards with the twelve replacement components were then sent to an independent lab for cross section analysis.

Cross Section Analysis

Sites #1-4 on the baseline board all showed good results. No underfill was used and no milling was done on these sites. Sites #1-4 were reworked in the traditional fashion on a BGA Rework Machine.

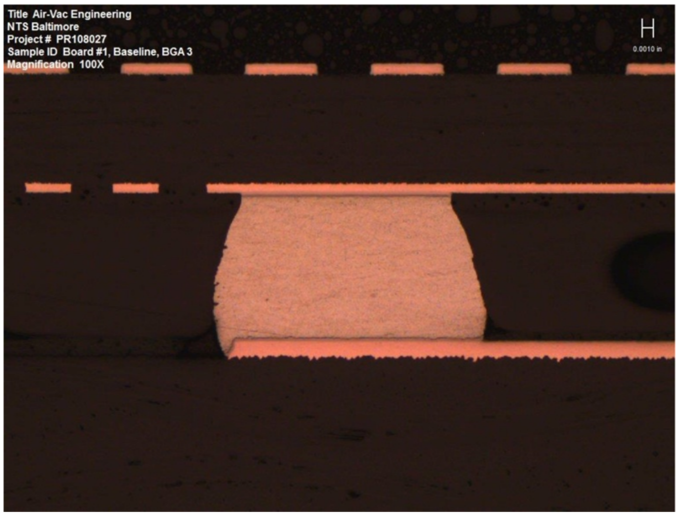

Figure 21 – Cross Section of Solder Joint on BGA#3 on the Baseline Board (no Underfill or Milling).

The majority of the eight BGA's that were replaced on the underfilled sites after milling had head-in-pillow defects that resulted from the non-coalescence of the solder balls on the replacement BGA's with the 0.13mm (0.005 inches) of solder that remained on the pads after milling.

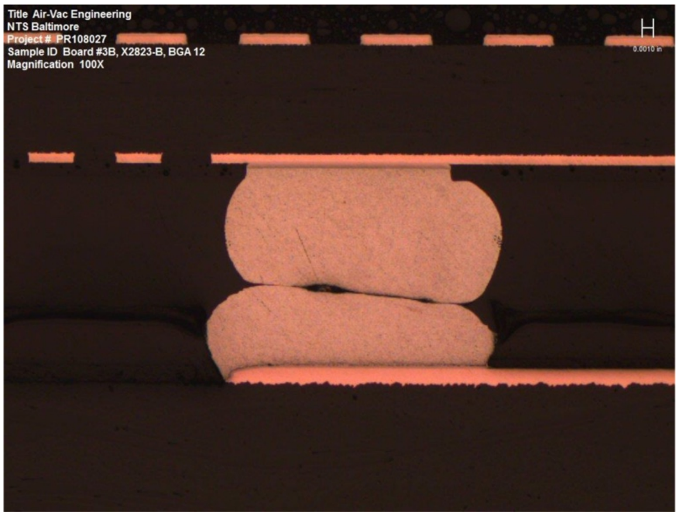

Figure 22 – Head-In-Pillow Defect

There are two main causes of head-in-pillow defects; poor wetting and board/component warpage. Poor wetting is a result of a sub-optimal thermal profile, insufficient fluxing or solder ball oxidation. In this case, it was determined that the thermal profile used to replace the eight BGA's on the underfilled sites that were milled needed further optimization. Phase 2 of this study, which is now in process, will be a duplication of Phase 1 but it will include the optimized thermal profile to replace all twelve BGA's.

Good cross-section results were achieved on several BGA's that were replaced on underfilled sites that had been milled. Figure 23 below shows a cross-section of a replacement BGA on a non-underfilled/non-milled site on the baseline board compared to Figure 24 which shows a replacement BGA on an underfilled site that was milled. The average height of the cross-sectioned solder joint on the baseline board is 0.3mm (0.01165 inches) compared to 0.4mm (0.0154 inches) on the underfilled site that was milled.

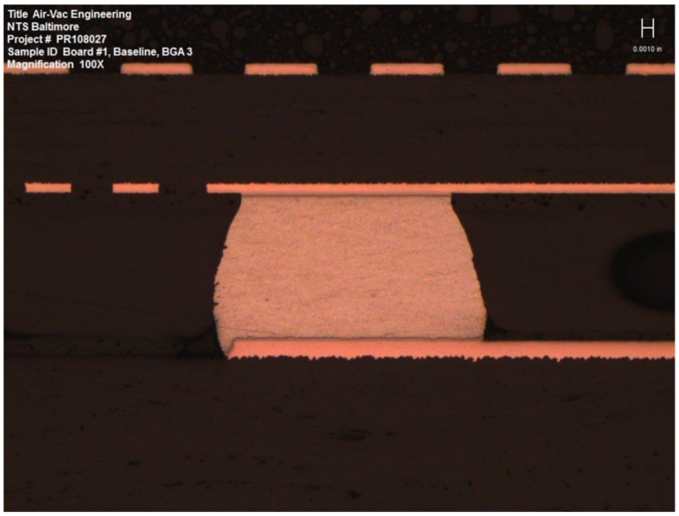

Figure 23 – Replacement BGA on Non-Underfilled/Non-Milled Site

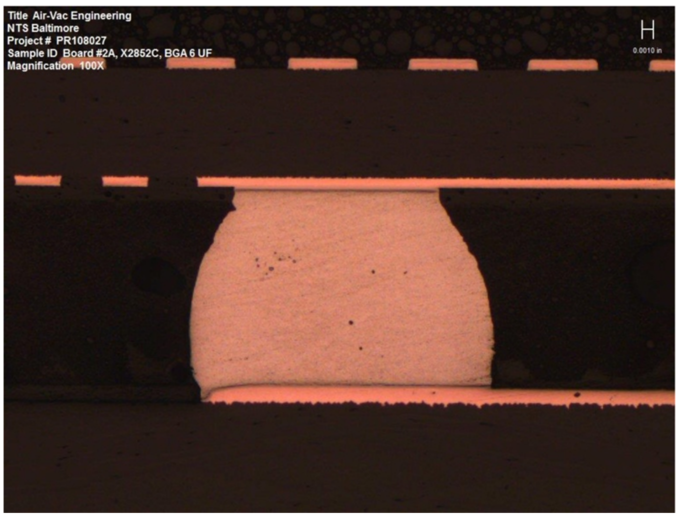

Figure 24 – Replacement BGA on Underfilled Site that was Milled

Summary and Findings

BGA and CSP technology is used extensively in high performance applications that require high pin count components in small form factors, however, the addition of underfill is required to provide the level of reliability that is required when these components are subjected to high thermal or mechanical stress.

One downside of underfilling BGA's and CSP's is that it makes the rework process extremely difficult or impossible based on the underfill composition that is used. Rework cannot currently be done when non-reworkable underfill is used.

Current rework processes for underfilled BGA's/CSP's typically involve multiple manual heating processes that lack process control and subject the underfilled site to potential damage.

A new approach for reworking underfilled components is to use a high precision milling machine designed specifically for milling electronic components. Unlike CNC-based milling that requires CNC programming knowledge and an expert machinist, a component milling program can be developed by a process engineer and executed by a rework operator. The small footprint, 110-volt power requirement, lack of lubricants and its proprietary vacuum capture system in a static-free enclosure allow the new milling machine for electronic components to be located in the rework area(s) of the factory.

The new milling machine has all of the critical features needed for effective milling of underfilled components on populated printed circuit boards, including underfilled components with zero adjacent clearance.

This machine brings automation and process control to the underfilled component rework process which includes milling both reworkable and non-reworkable underfills. The precision milling approach involves no heating of the component or the site compared to multiple, manually controlled heating cycles.

This new process mills off the entire component and 90+ percent of the underfill and the solder on the pads leaving approximately 0.13mm (.005 inches) of underfill on the site and solder on the pads. The solder joint of a BGA/CSP that is replaced on a milled site will contain a higher volume of solder than a BGA/CSP solder joint that is replaced on a non-underfilled site unless solder paste is added to the component or the pads. The larger volume of solder in each joint should result in increased component reliability.

Initial cross section results showed a high incidence of head-in-pillow defects where components were replaced on milled sites. It is believed that an optimized thermal profile will correct this issue. Phase 2 of the Milling Study includes an optimized thermal process and is already in process.

Milling tests have been conducted on approximately ten customer boards in 2019, all with good or promising results, but only with small sample sizes due primarily to limited board availability. Significant additional in-depth milling tests will be done in 2020 on a wide range of components and printed circuit boards with multiple reworkable and non-reworkable underfills from several suppliers. Thermal and mechanical stress testing must also be performed.

It is expected that some combinations of components, boards and underfills will require a site preparation step to be added after milling. Site preparation testing using a proprietary site cleaning nozzle has already been conducted. This process removes the 0.13mm (0.005 inches) of solder that remains on the pads after the milling process is complete, but it does not remove the 0.13mm (0.005 inches) of underfill that remains on the site. This results in underfill "pockets" that surround each pad.

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