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Selective Reflow Rework Process

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Abstract
In the rework environment, most equipment and procedures are designed for low volume repair/rework process. When a high volume rework is needed, the challenges begin. For example, a long cycle time is required to perform ball grid array (BGA) rework. When we need to remove material, do pad dressing, pad inspection, paste printing and place a new BGA, those steps increase the amount of dedicated rework equipment. Some machines are used to remove material, others are used to do pad dressing and others to place a new BGA. This results in hundreds of rework tools and equipment on the production floor. That volume of rework consumes enormous amounts of resources, requiring process controls such as daily profiling and maintenance using excessive hours of human resources. In addition, the standard rework process has low yield and high scrap rates.

The Selective Reflow Rework Process is an approach to improving the high volume rework process, increasing process capabilities and process repeatability by using a standard reflow oven of 12 zones, pick and place machinery, semi-automated printing gear and Solder Paste Inspection (SPI) implementations. This approach was able to reduce the amount of rework equipment by more than half. Our human resource requirements (indirect and direct labor) were cut by more than 50% and our rolled throughput yield increased from 68.9% to 84.14%. The Selective Reflow Rework Process is less reliant upon operators and has become a repeatable, stable rework process.

To obtain this advantage and have a successful implementation of this technology, the process requires new controls for printing, and check points before proceeding to the next process step. The printing process has a major impact on the HiP reduction, optimizing solder paste transfer efficiency (TE) and establishing a real SPC that gives real time warnings of anomalies. By identifying challenging process key parameters, including paste height, printing technique, pallets design and thermal barrier protection of TH parts, this paper will discuss some aspects of the process optimization and changes made to improve the quality of the rework process.

Key Words: Selective Reflow, rework, HVLM (High Volume Low Mix), BGA (Ball Grid Array), HiP (Head in Pillow), Stencil, PCB, TE (Transfer Efficiency), SPC (Statistical Process Control), IPA (Isopropyl Alcohol), SPI (Solder Paste Inspection), DL (Direct Labor), IL (Indirect Labor), TH (Through Hole).

Introduction

The rework of field failures requires several steps (Fig. #1), the first being the debug process. Once the issue is determined, a disassembly process is needed to take apart assemblies, including chassis, plastics parts and TH components. Most of the parts can be removed, with the exception of the soldered parts such as TH components. In this study, 93% of the failures were related to specific BGA with 1156 spheres or connections (I/O). The concentration of failures is mapped in Fig. #2.

The rework process to repair a BGA follows the same sequence as shown in the Figure # 1:

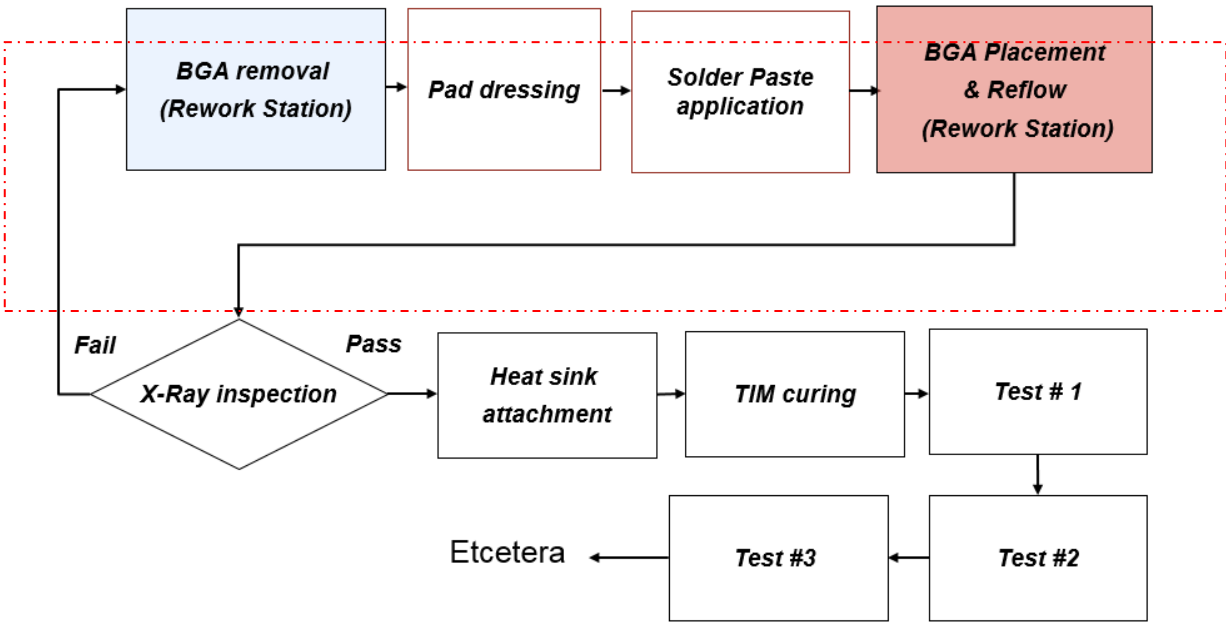


Figure # 1: The BGA rework process:
pad dressing, solder paste application & BGA placement were areas that required improvements

Figure # 2: Defect mapping

The Challenge: Production volumes were at 7,000 units per day; but our rework equipment could only remove 7 BGAs per hour or place 7 BGAs per hour. To meet the demand, we used 44 rework machines for removal, and another 44 to re-place new BGAs. The DL required to operate these machines was 54. Rework equipment required daily profiling to corroborate performance & weekly maintenance, which demands DL and IL engage three shifts, seven days per week.

Common rework BGA placing processes follow similar activities with rework machines:

- PCBA placement in the pallet
- Print paste then inspection
- Place the BGA using rework equipment alignment system (prism)
- Place protection fences or covers (to protect TH and plastic connectors that cannot withstand excessive heat, see figure #3)
- Start preheating stage

- Start profile subsequently until paste/ball reaches melting point to form the joint
- Cycle end, nozzle goes up and “cool down” starts (since we stopped the heating process). “Air” is blown through the hot nozzle to cool down the BGA & surroundings. This process is very inefficient and the joints suffered long times above liquidus (TALs).
- Remove protection covers
- Remove PCBA from pallet for X-ray inspection

Our rework rolled throughput yield (RTY) averaged 68.9%, increasing our resource requirements of machinery & personnel. High scrap rates and root cause failure analysis pointed to one component, which gave us the option to generate a proposal were we can speed up the rework process, reduce labor and equipment needs and increase yields by increasing the process repeatability.

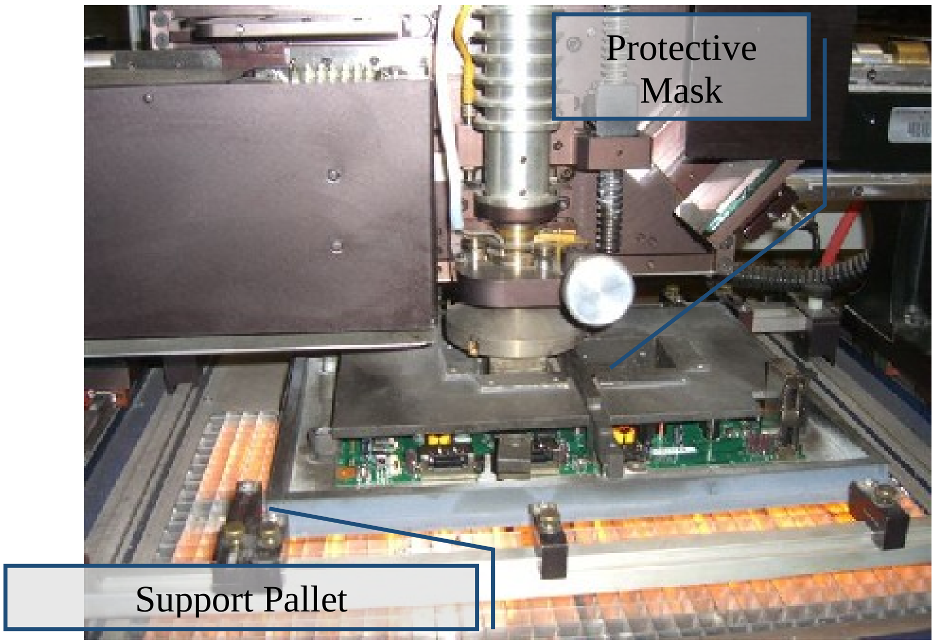
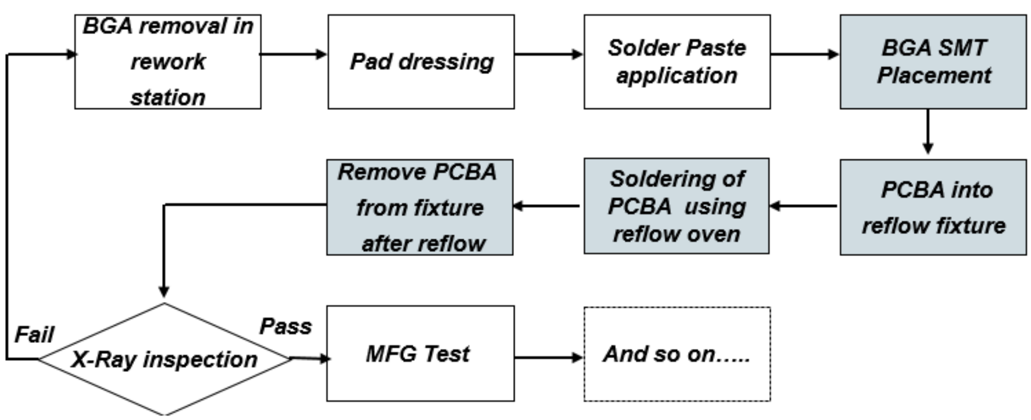
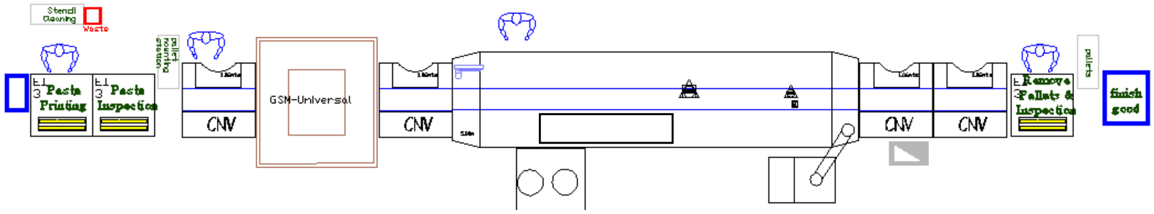


Figure # 3: The BGA rework machine process:
Protective mask for TH, plastic connectors and support pallet

Methodology

The process proposal was called the “Selective Rework Reflow Process” (see Fig. #4). The project had several objectives, among those was to improve yield by increasing process repeatability, reduce cost of machinery and personnel and increase overall performance of the rework process using an SMT approach.





Note: special pallets are required to make the process work in a continuous manner.

Figure 4

BGA Placement: The first challenge was to design a pallet that could fit in the SMT machinery for the BGA placement. Pallet maximum height was a restriction due the TH components that are already too high for the pick and place process. The pallet has a retractable central area that can move down, once it enters the SMT pick and place machinery (it goes up with the machine table movement). See fig.5. This helped us to reduce handling by using entrance and exit conveyors, avoiding a manual loading into the machine or removing the tallest TH component. The machine clearance requirement was 53 mm.

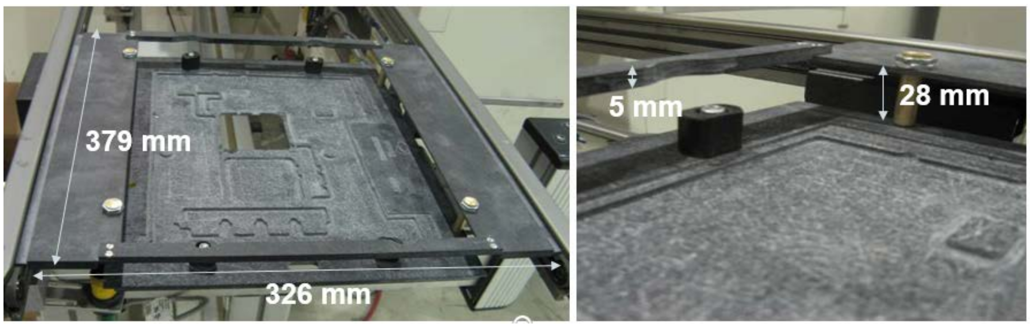


Figure # 5: Bottom side of the pallet for the selective reflow rework process

Once the height requirements for entry were addressed, pick and place using the camera and material in a tray resolved all placement & handling issues with the common rework process (rework prism alignment and placement has human interaction to handle and place BGAs).

Reflow Fixture: the second difficulty was the thermal protection for TH and plastic connectors to tolerate the heat from the reflow oven, without affecting the BGA soldering process. A special coating was added to the pallet to reduce the heat transfer. See Fig. 6.

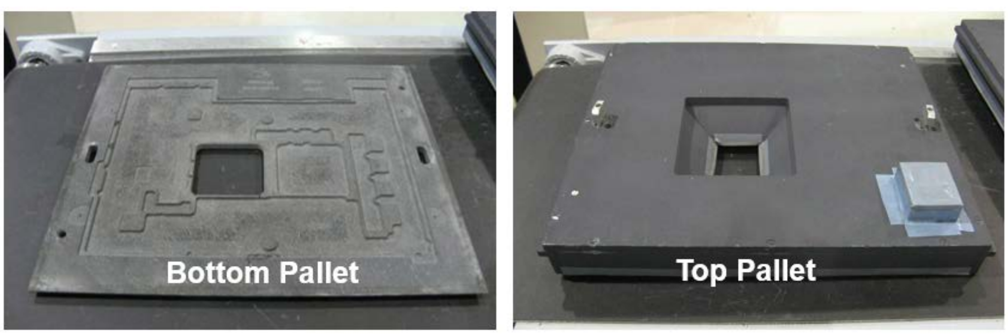


Figure # 6: Reflow protective fixture

The protective fixture required several design considerations - the bottom support needed to be deep but avoid touching the bottom side components with the pallet, yet give enough PCBA support to reduce warpage. The top cover had to protect the TH & connector components and leave open the BGA area to be soldered.

Soldering: The third major matter was profiling to achieve several requirements; at one end were components that could not withstand more than 150ºC, and at the other end, the BGA to be soldered. After several trials and DoE's, a cover redesign and change of protective materials, we found a less problematic profile. The main issues with this type of BGA were HiP (head in pillow). The typical profile used is shown in Fig. #7. With the change from standard rework equipment to reflow oven, the entire process improves by increasing repeatability of profiles and placement. Rework equipment has only one heating element and convection heat transfer, depending on the air pressure of a pipeline or pump (for some rework machinery). The 13 zone reflow oven has really 26 zones (13 top & 13 bottom), each with independent heat elements. Forced convection is made through two fans per zone, giving a wider process window to achieve soldering specs from BGA & paste. A profiling board has four thermocouples at BGA corners, plus five additional thermocouples in TH components and plastic connector bodies. In Fig. #7, the thermocouples with lower heat (lower than 150ºC, at the low area in the graph), are underneath the protective cover measuring TH parts. Thermocouples with ups and downs were at the corners of the BGA.

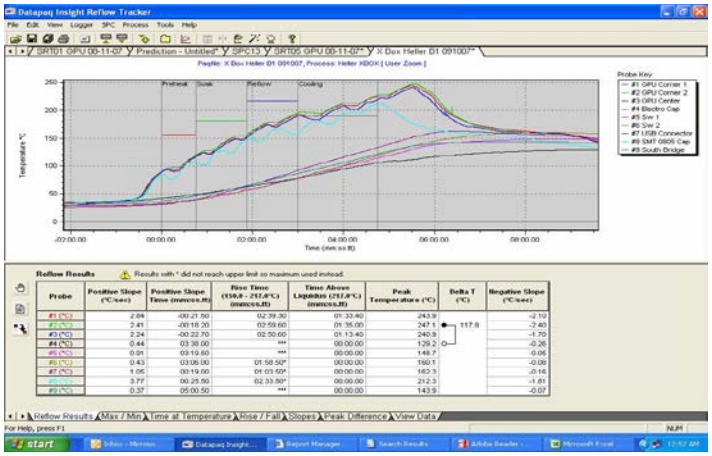


Figure # 7: Reflow profile "typical shape" for selective rework reflow process

Data Analysis

Once the selective rework line was able to rework BGA without damaging other TH & connectors, the fine tuning process began based on failure modes. If tests correlated the failure with the BGA, x-ray & failure analysis of dye & pry technique were used. The most common failing mode was openings due to Head in pillow (HiP).

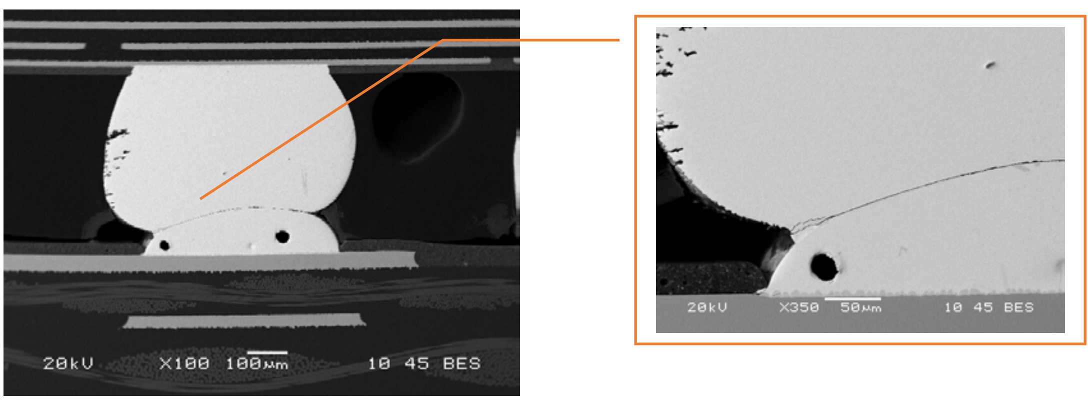


Figure # 8: Cross section SEM image of a "Head in Pillow" found in one of the reworked BGAs

Variables analyzed started with stencil thickness (paste height), stencil opening, printing technique, printing tooling, type of paste, mesh type (3 vs.4), profile type (heating ramp rate), TALs and peak temperature were submitted for analysis.

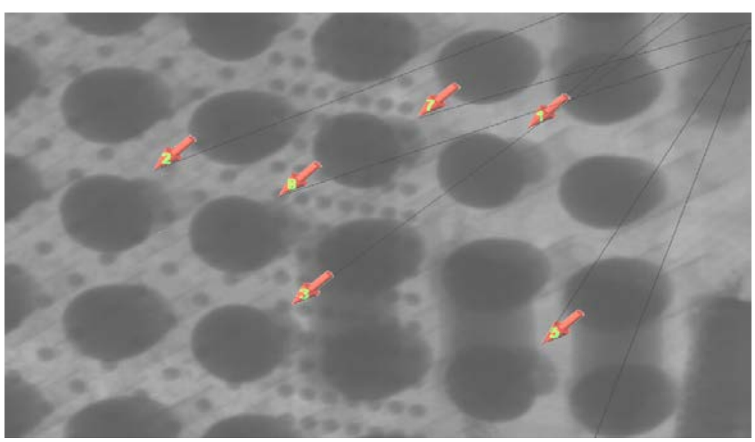


Figure # 9: X ray images can detect HiP. Some HiP's are hard to catch. Inspector skills and tilt x- ray capabilities are needed

Dye & Pry FA techniques help us understand critical areas and important variables. Defect mapping (see Fig. #10) was made by BGA pad, since 1156 BGA balls were involved in the rework process. The goal was to achieve 100% of solder joints.

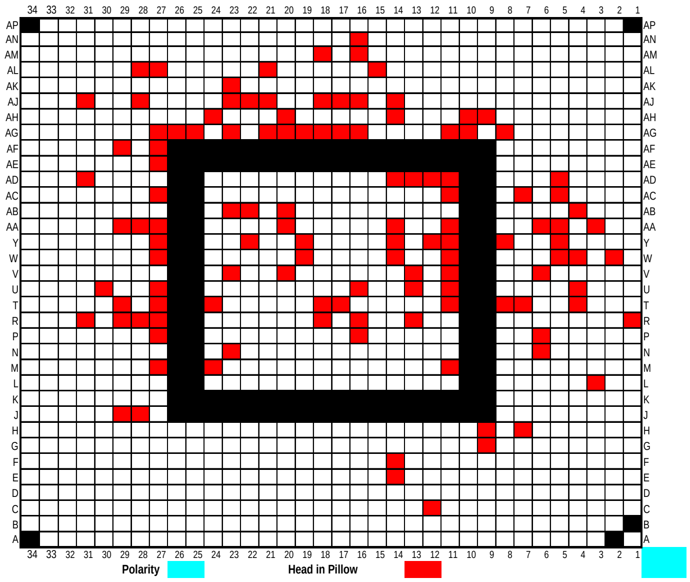


Figure # 10: Example of HiP defect mapping tool used for 1156 connections

The HiP main characteristics always appear at BGA ball concavity form on the bottom side of the ball while paste solder takes a "dome shape" in the PCB pad (solidified solder paste printed).

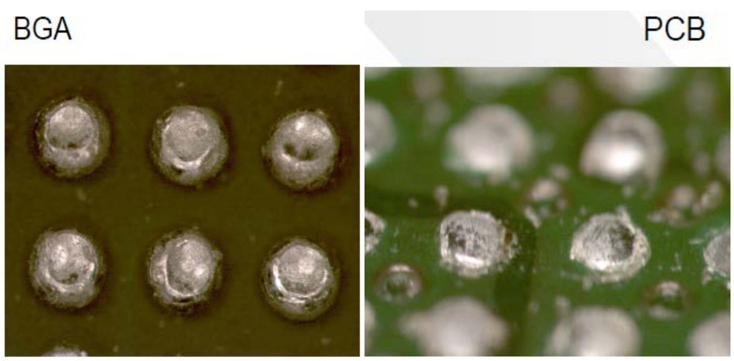


Figure # 11: HiP defect after BGA rip off. Right side is the bottom side of the BGA showing the concavity.

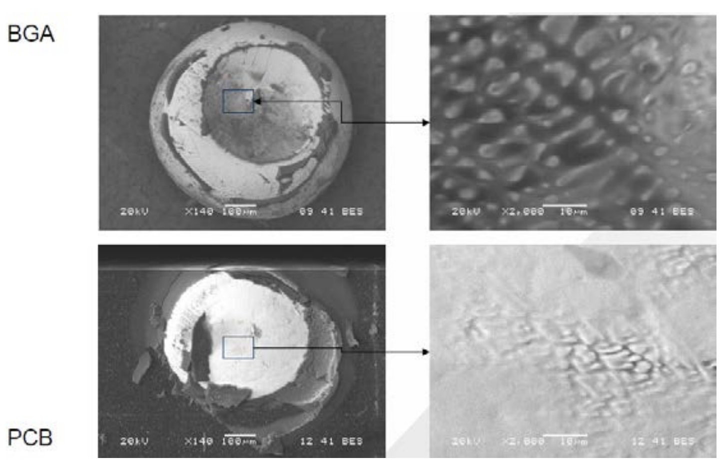


Figure # 12: SEM images of a HiP, no metallurgical incompatibility found, no foreign material found in the EDX analysis.

DoE's were done to check the solder compatibility between paste and solder balls, type of paste with more aggressive fluxes, better tackiness was tested, to find out any metallurgical inconsistency/incompatibility that may provoke those HiPs. See Fig. #13 for reference to one of the runs established.

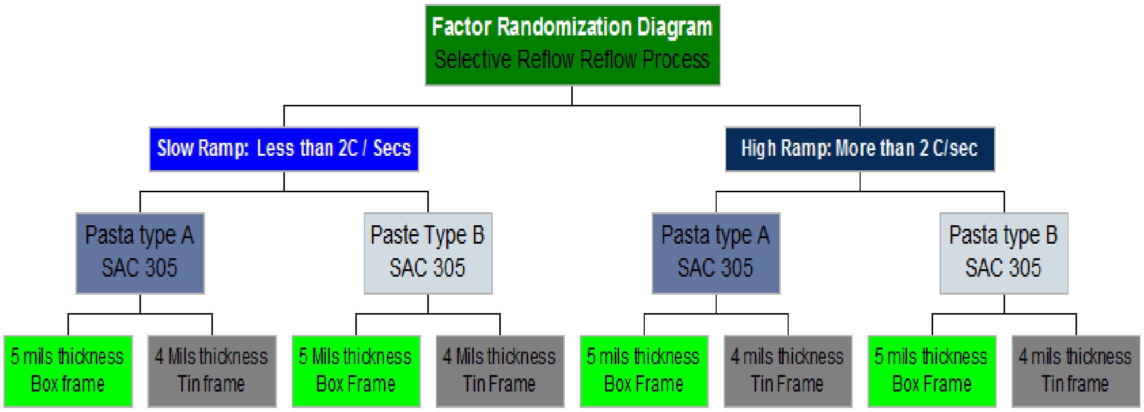


Figure # 13: Example of one of the several DoE's made (Factor Randomization Diagram) to analyze metallurgical incompatibility

From those studies, it was determined that paste type has little effect on the equation. On the other hand, profile peak temperature, paste height (rather than paste volume) and consistency of paste printed were the main contributors to the HiP formation.

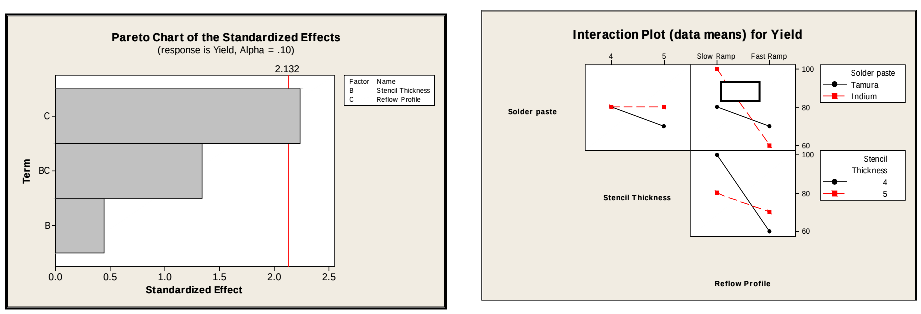


Figure # 14: Main contributors' profile and stencil thickness from DoE #5

Paste height resulted in more sensitivity to failure when we had lower values, and profile peak temperature in combination with heating rate promoted the HiP defects (see Fig.#14), based on the results from several analysis and profiling DoE's. The results showed better performance using profiles with peak of 248º C rather than lower peak of 238ºC, and even better results were achieved with profiles of 253ºC peak temperature with slow heating rates. To better comprehend the BGA warpage phenomenon, a Thermoiré test was made over the BGA to understand the warpage behavior at different peak temperatures and different heating rates.

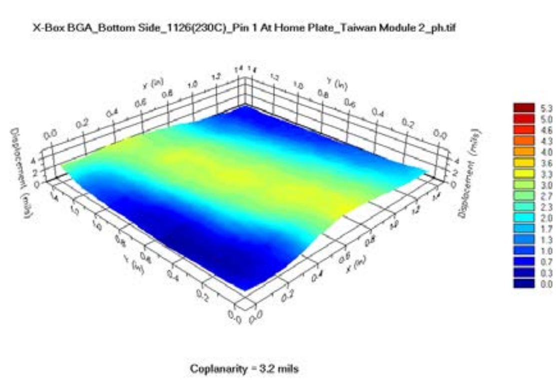


Figure # 15: Thermoiré image of the bottom side of the BGA showing a coplanarity of 3.2 mils along all BGA Ball at 230ºC

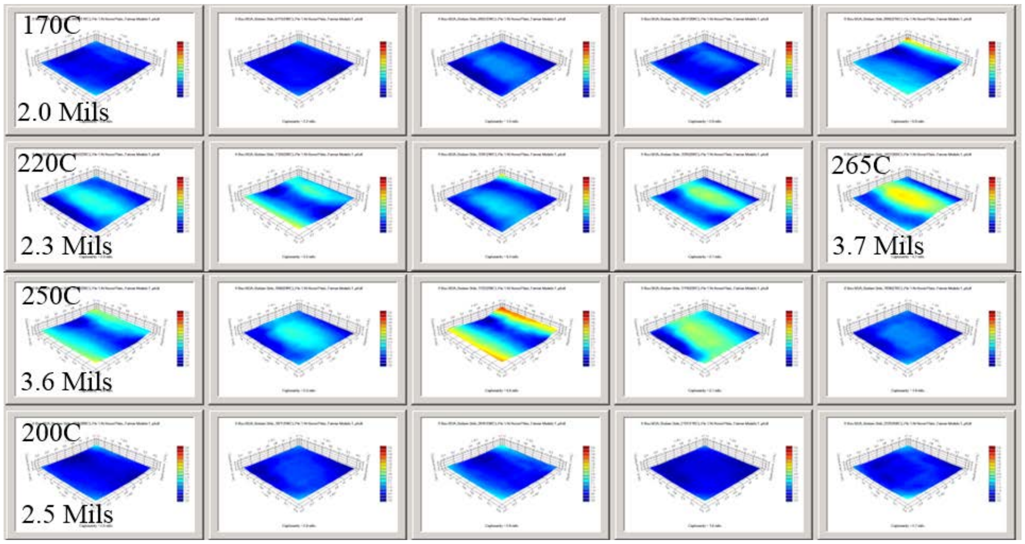


Figure # 16: Thermoiré images at every 10 degrees showing BGA behavior under thermal stress

The BGA ball coplanarity study was made to see solder balls' flatness plane or sitting plane. The height range of solder balls from one date code shows height variations as high as 0.11 mm (4.4 mils).
Note: range is understood as the difference between the tallest and the shortest BGA ball heights

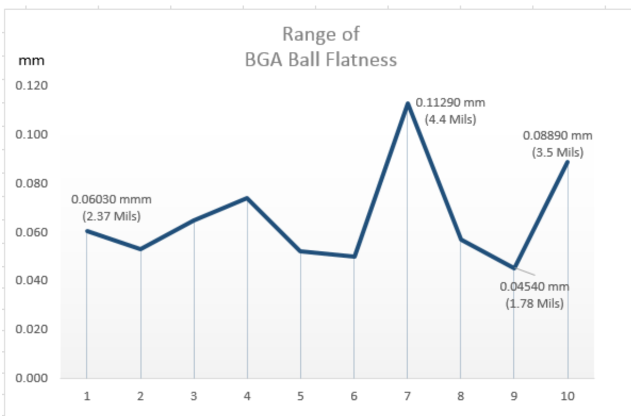


Figure # 17: Range height measure per sample. Major height found at 0.112 mm (4.4 Mils)

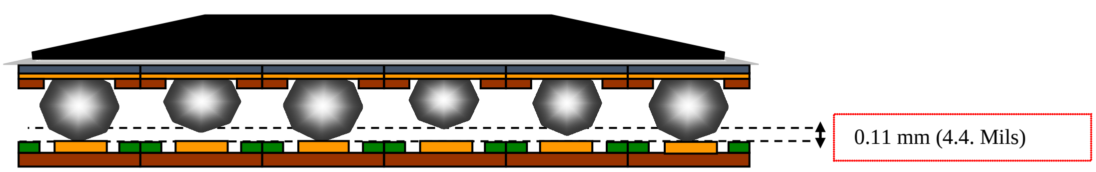


Figure # 18: Solder ball range height explanation, changing the sitting plane

With regards to warpage, the critical area that affects the solder formation in the profile is after peak temperature close to melting/solidification range. When the molten solder and partially melted ball are mixed, there's no longer pure SAC 305 - the Cu and plating's dissolution affect alloy and solidification range. At this profile stage, most of the flux activators are gone and only the superficial tension forces keep the molten paste united with the solder ball, if that joint is still there. Paste in molten stage will easily lose 50% of the original paste height. Add to this the component warpage, the BGA ball sitting plane height range and a uneven paste deposit height, and a ball-paste joint separation is produced. BGA warpage will lessen when thermal stress goes down (at the cool down profile area, after peak temperature), returning to the original flat shape. The problem is that mass differences between BGA ball and solder paste deposit is just too much. In this case, molten solder at the pad will solidify first (smaller mass), then a few seconds later, the BGA with a semi solidified solder ball returns to a flat shape to form the solder joint. This is the main reason why the pad paste deposit always takes the shape of a dome, and also the reason why we see a cavity in every solder ball with the HiP phenomenon. In this analysis, our HiP is not a metallurgical problem, but rather a mechanical issue due to several process variables and conditions. Consequently, is this phenomenon really a "Pillow in Head?"

Table #1: Rework Processes and consequences that generate HiP

Process	Variable	Reduce or Increase HiP	Process opportunity
BGA Soldering	Thermal stress	Increase	Yes
BGA low T_g	Low transition temperature	Increase	No
BGA coplanarity	Wide sitting plane	Increase	No
Paste Printing	Add solder to form the solder joint	• Poor printing: Increase Good printing: Reduce	Yes

Figure # 19: Process variables that promote the HiP:
Coplanarity condition + Thermal stress that produce BGA body warpage = promote HiP

The selective reflow rework process dramatically improves the BGA placement & soldering process, reducing the heat-affected zone with better thermal protection for TH parts. That helps to increase yield, and the HiP phenomenon was reduced but not eliminated from the process. After understanding the options we had on our hands to reduce the problem, the team started to understand the printing process variables. Manual paste printing has always been the way to do this paste printing rework, so our analysis involved spatulas types with different widths, stencil thickness from 4, 5, 6, 7 mil, and with a step-up at the central area.

Printing variables - with 1 stroke vs. 2 strokes, left or right, up & down or just up, etc. - were also studied. Stencil frames - height and shape - and even stencil ejection fixtures were tried in order to improve the paste height uniformity. (See Fig. #20).

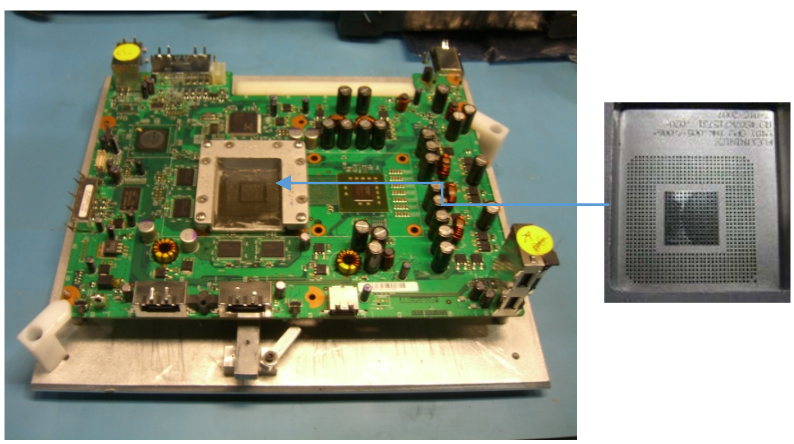


Figure # 20: Support fixture for manual paste printing, with ejection mechanism for stencil frame.

Early on, the first studies showed that the manual printing process was out of control - low repeatability along the shift and between shifts, operator A performed differently from operator B, and so on. Fig. # 21 shows process inconsistencies with Cp / Cpk at 0.63 to 0.61. Paste height ranges from 0.11 to 0.2 mm (4.2 to 7.8 mils).

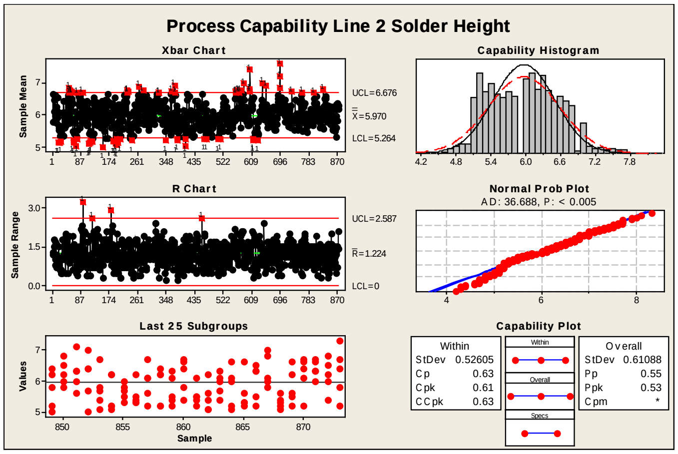
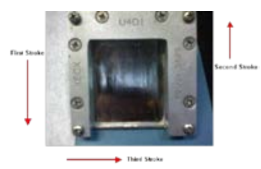
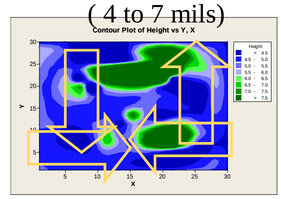
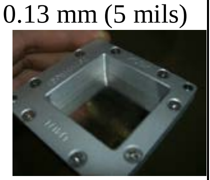
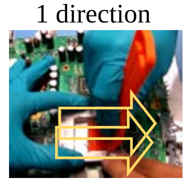
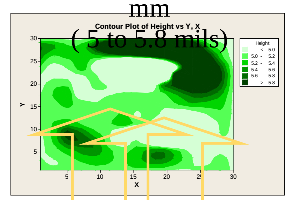
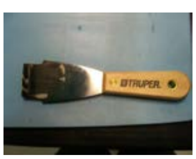
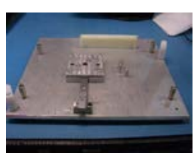
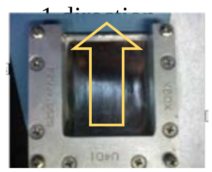
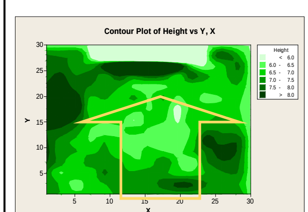


Figure # 21: Early manual printing performance - the process is not standardized

The printing technique changed along the way - paste height was increased from 0.102 mm to close to 0.178 mm (from 4 to close to 7 mils). Some of the trials made in an effort to come up with the best process are shown in table #2**:**

Table #2: Some of the manual printing efforts with some variables

Tooling (spatula)	Stencil	Support fixture	Technique	Result
	0.1 mm (4 mils) 		4 strokes 4 direction 	Height range: 0.1 0.18 mm (4 to 7 mils) 
	0.13 mm (5 mils) 		2 strokes 1 direction 	Height range: 0.13 0.15 mm (5 to 5.8 mils) 
	0.15 mm (6 mils) 		1 stroke 	Height range: 0.15 to 0.2 mm  (6 to 8 mils)

Operator dependency is always high in this type of manual printing process, the height changed by operator/shift/day. This aspect became more important when a correlation was found between paste height and HiP. Paste height lower than 0.16 mm (6.3 mils) has more probabilities to produce HiP, so become our LSL and the maximum paste height allowed (USL) was set at 0.191 mm (7.5 mils).

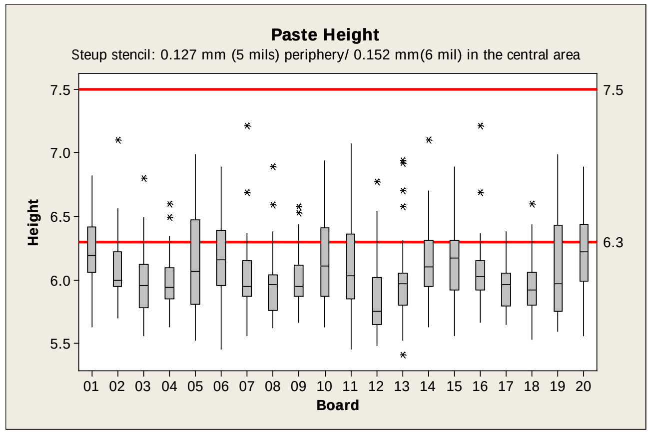


Figure # 22: Manual printing run using step-up stencil (0.127 to 0.152 mm at central area [5Mils to 6 Mils]) LSL of 0.16 mm (6.3 mils) to avoid HiP and USL of 0.191 mm (7.5 Mils).

The engineering staff worked to reduce the dependency on labor, and an automated approach was taken to aid operators in the printing process. The first prototype had a pneumatic piston that moved up & down the stencil, while in another the piston printed. Operator assistance was needed at the end of the printing process, for removing the paste at the end of each squeegee stroke and moving the paste back for the next print.

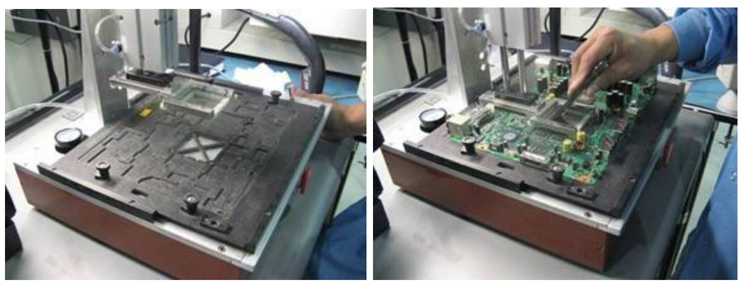


Figure # 23: First prototype of the semi-automated printer

The printing behavior improved, reducing the process variability and producing evenly deposited paste along the 1156 pads. This helped us to control process, producing less and less HiP defects. The semi-automated machines improve the effectiveness up to 95%, reducing misprints and printing stations.

Ultimate and actual design can control: Input pressure, solder printing speed, stencil release speed & printing spatula pressure over the stencil. Process variability was reduce to levels that can repeat through shifts & days independently of operators.

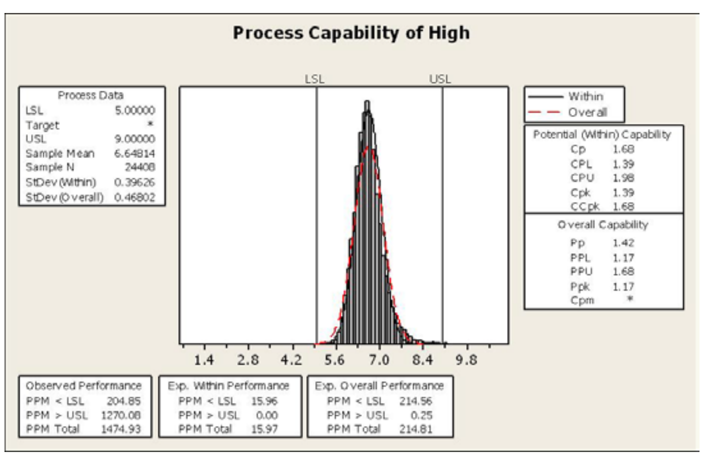


Figure # 24: Pneumatic printer produced printings with low dispersion of paste height using a flat stencil thickness of 0.152 mm (6 mils) with 0.457 mm (18 mils) round apertures

Results

By improving the profile's repeatability (peak, times, and slopes) using a selective reflow rework process (SRRP) that uses reflow ovens on 13, we were able to improve the quality of the solder joints. This was mainly done with the profiles having at least 100 seconds above liquidus. Standard rework profiles with the pallet and the protective mask generated TALS of 120 to 150 seconds. The IMC thickness moved down from 10 microns to 6.3. (See Fig. #25)

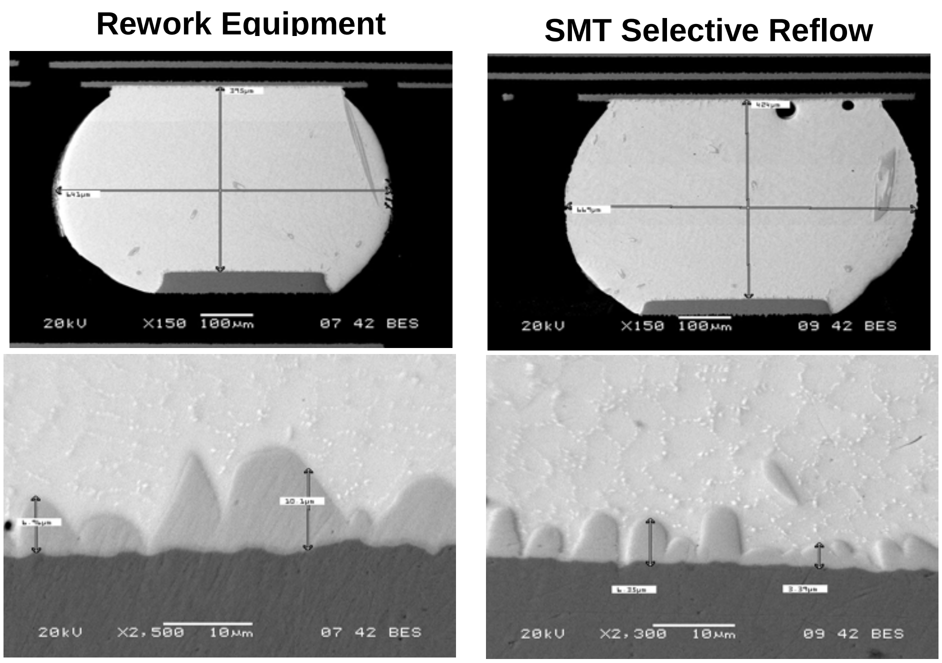


Figure # 25: Intermetallic compound layer (PCB side) show less aggressive shape and less thickness using the selective reflow rework process

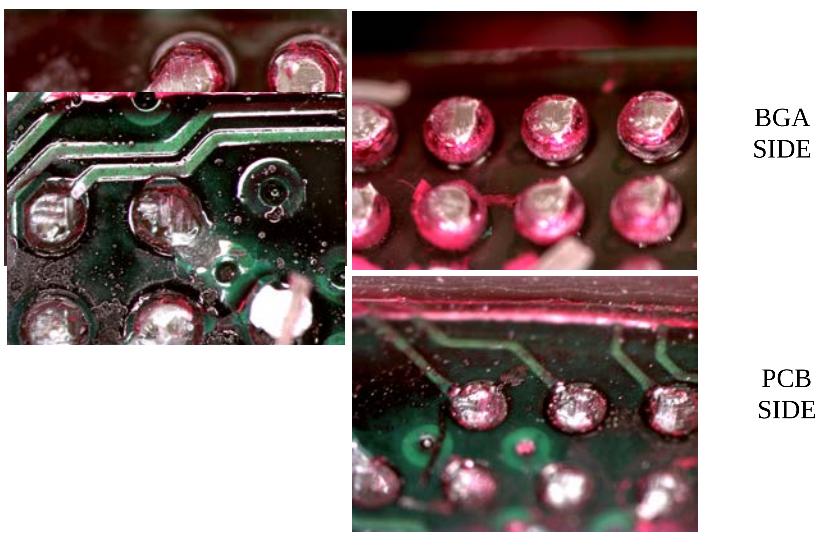


Figure # 26: Dye and Pry images from BGA & PCB side, with no penetration in the solder joint

Quality prevention checkpoints include an SPI after paste printing, height values lower than 0.10 mm (6.3 mils) were rejected, taken apart, cleaned and printed again. Values higher than 0.191 mm (7.5 mils) also got rejected but for bridging concerns.

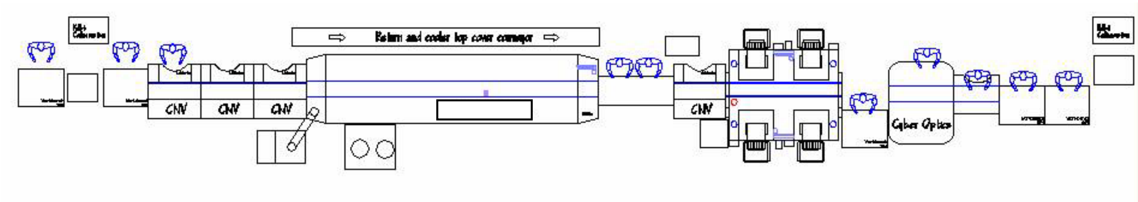


Figure # 27: Selective reflow rework line configuration. SPI in line and a cooling zone for pallets were added to improve UPH

With regard to process repeatability, machinery requirements, cost of equipment, space needed, DL engagement and process challenges, an estimation is shown in Fig. # 28. Fulfilling a daily capacity of 6,000 units, the new process needs just 45 standard rework machines to place the BGAs, and only 2.5 selective reflow rework lines are required.

Capacity Analysis SMT Selective Reflow vs. Std. Rework						
			Month	JANUARY		
			Weeks	W01	W02	W03
			Volume	42000	42000	42000
Operation	Time per board (Sec.)	Rate/Hr	Rate/Day	7	7	7
Selective reflow rework Lines	27.0	126.7	2422.5	2.5	2.5	2.5
Std. equipments to Reflow	435.0	7.0	134.5	44.6	44.6	44.6

Figure # 28: Capacity analysis in UPH: 4 4 std. rework machines are needed to place BGAs vs. 3 selective reflow rework lines

As the units start to move from standard rework equipment to the selective reflow rework process, Rolled throughput to Yield (RTY) moves up. On average, standard rework has a RTY average of 68.8%, while the selective reflow rework line has an average RTY of 84.14 %.

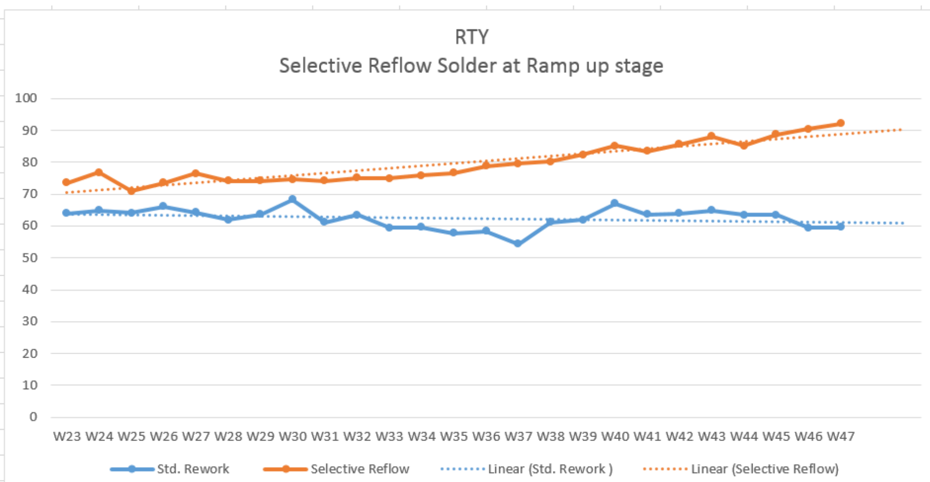


Figure # 29. RTY comparison between Std. rework and Selective Reflow rework process

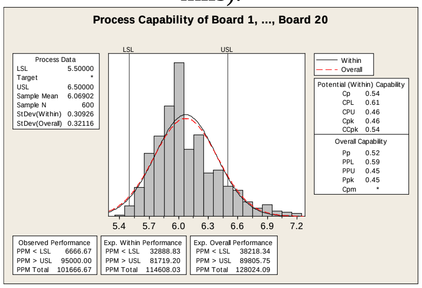
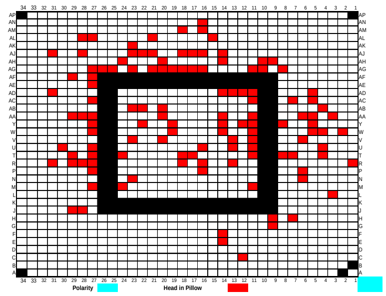
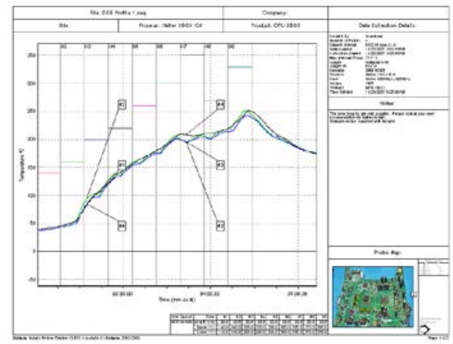
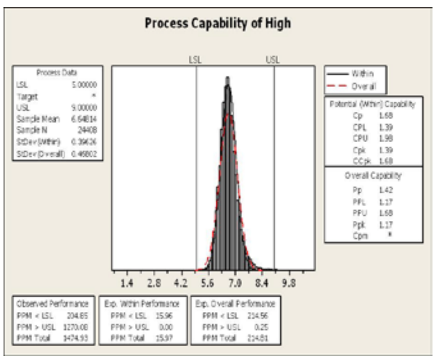
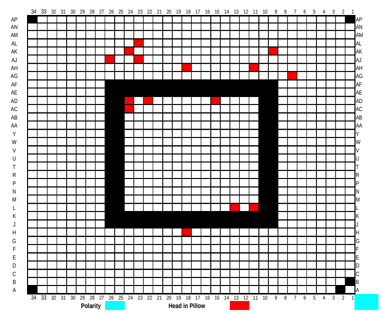
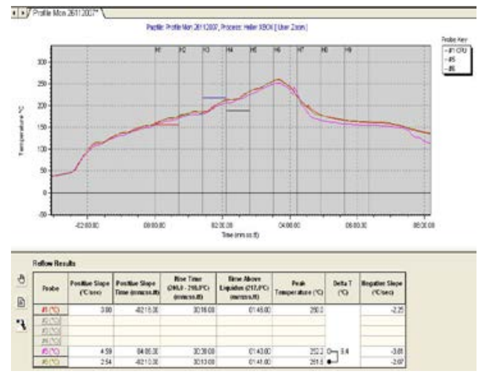
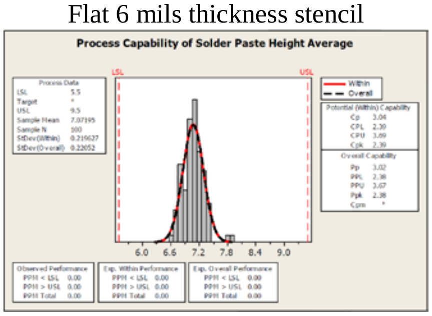
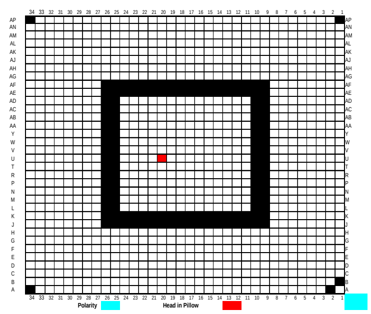
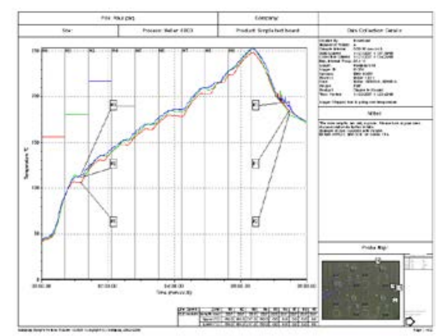
Event	Paste dispersion	Defect mapping (HiP)	Profile
DoE run on Dec .12.	Flat stencil of 0.14 mm (5.5 mils) central area, periphery of 0.127 mm (5 mils). 		
DoE run With proto Semi-automated printer	Flat 5 mils thickness stencil 		
Last event before process launch With Semi-automated printer	Flat 6 mils thickness stencil 		

Table #3: Summary of variables that affect the yield loss are mainly related to HiP phenomenon

Summary

The Selective Reflow Rework Process (SRRP) increases process repeatability - in the early stages of ramp up, the project was successful in increasing the rolled throughput yield by 15 points. Our production costs were reduced, and DL was optimized by 50% by replacing 50 standard rework machines with 3 SMT lines for the selective reflow rework process.

Conclusions

While several factors affected the yield in our field failure rework units, the main contributor to yield loss was HiP (head in pillow). From this research, the following conclusions can be made:

- BGA placement and reflow become a steady process using the SMT machinery - little human interaction affected the process
- One of the main variables that became significant was the profile (affecting the BGA warpage). Profiles with peak temperatures close to 253ºC produced less HiP defects.

- Manual paste printing was the major variable that aided or instigated the HiP effect Automation of the process minimized variability, increasing the yields
- Paste height lower than 0.16 mm (6.3 mils) is more likely to produce HiP, while paste height above 0.191 mm (7.5 mils) increases the risk of solder bridges
- Component warpage under thermal stress combined with solder ball sitting plane height created a large gap, and printed pastes became too sensitive to promote or reduce the HiP
- The HiP phenomenon is not a metallurgical issue, but rather a mechanical/thermal problem

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- Milpitas, California corporate AEG – Dason Cheung, Ph. D. Jane Feng & Murad Kurwa

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