Hot Air BGA Rework Process Improvement with a Touchless Temperature-Dependent Live-Feedback Process

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Abstract
Commonly used integrated circuits have been increasingly moving from leaded packages that are reworkable with a soldering iron to leadless packages such as BGAs that require complex rework that cannot be visually inspected to confirm success. BGA packages have been decreasing in ball spacing (pitch) and increasing in I/O (ball count) making commonly accepted/documented time-dependent hot air local reflow profile development techniques no longer optimal. At the same time, the complex PCB interconnect structures (and resultant sensitivity to thermal cycles) needed to support these packages drive a need for tighter process control which is not attainable by using the classic time-dependent reflow profile. These factors combine to drive a need to improve the supporting processes around complex hot air rework. This paper addresses that need by providing:

- Background on prevailing standard practice time-dependent hot air reflow profile development and practical usage
- Summary of efficiency challenges and risks to achieving strong process control using this standard practice
- Explanation of a live-feedback touchless temperature-dependent reflow profile development and usage, including efficiency improvements created during development processes
- Experimental evidence demonstrating improved process control from a temperature-dependent live-feedback profile methodology
- Reviewing real-life risks (using FMEA-based thinking) and showing the increased variability tolerance to these using a temperature-dependent profile relative to classic time-dependent profile
- Practical manufacturing efficiency improvements gained by this updated basis of profile tracking

The overall goal of this paper is to share our complex rework process improvements for our colleagues in the electronics manufacturing industry to review and consider how incorporating into their practice can provide benefit to them as well.

Introduction; Challenge of Hot Air Rework Processes Today
Many in the industry, ourselves included, have experienced that hot air rework can be challenging and lead to variable results that require monitoring by X-ray analysis to determine success. We have historically made significant effort to create reflow profiles to achieve key soldering criteria of Time Above Liquidus and Peak Temperature. However, even with this effort we would see instances of X-ray inspection showing poor results driving repeated rework cycles. This led us to rethink our process and the existing sources of variation and then search for improvements. This paper details our methodology, solutions tried and implemented, and the gains achieved.

In today's most commonly accepted industry practice (see reference 1, 2) hot air reflow profiles are a series of steps of varying hot air nozzle parameters of air temperature and air flow over multiple steps delineated by set lengths of time. The outputs of the nozzle and the length of time for each step's duration are adjusted in order to achieve the desired temperature profile over time monitored at target location. Figure 1 illustrates a configuration to generate a classic time dependent BGA reflow profile. TC1 is a wide-angle IR sensor that is used to measure and monitor PCB's average temperature. TC2 is a thermocouple wire sensor embedded to touch a BGA ball from a scrapped PCB backside. It measures the BGA ball temperatures and its reading is used as the BGA reflow temperature target.

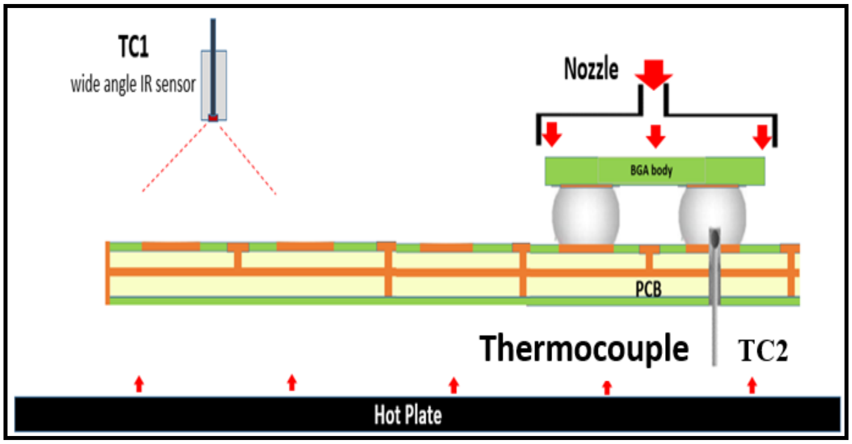


Figure 1 - Configuration of classic time dependent profile generation

The nozzle and hot plate output temperatures are typically set up in steps named as Preheat, Pre-Soak, Soak, Ramp, and Reflow. Each step is controlled by time in seconds. Figure 2 illustrates a typical time-controlled profile (Tin lead) generation.

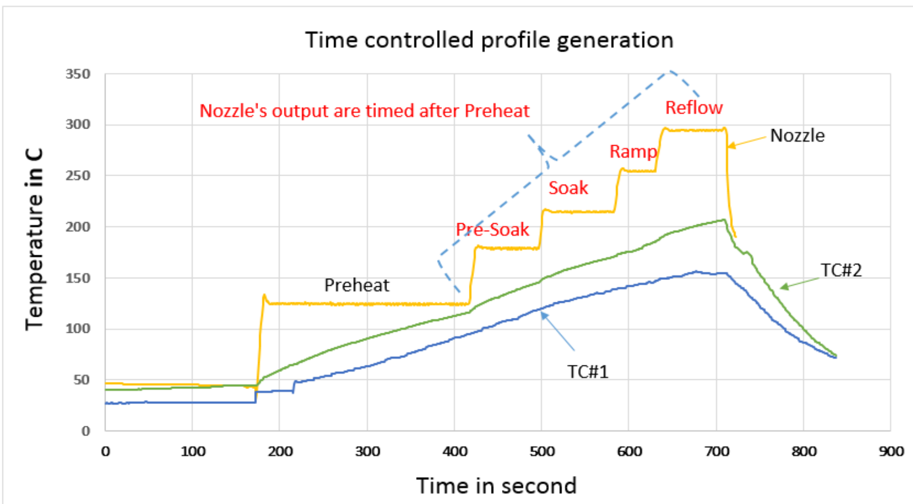


Figure 2 - Typical time-controlled profile generation

During the Preheat step, the nozzle outputs fixed temperature hot air until TC1 reaches the preheat target. After preheating, the nozzle's outputs are timed at each step from Pre-Soak to Reflow, increasing at each step. In the profile generation process, nozzle temperatures and times are adjusted, and profiles rerun until TC2 reaches target reflow profile. We then record the generated profile and reuse it in real rework. The newly generated time-controlled profile is only good for above specified card and device location. More new profiles are required if a BGA size, populated location, or PCB are different.

During an operational BGA device rework profile running, TC1 measures PCB's average temperature through the preheat stage and upon TC1 reaching the preheat target temperature the remaining steps from Pre-Soak to Reflow are initiated. Settings of both the hot plate and nozzle are controlled by the recorded profile through the Pre-Soak to Reflow steps including the duration of each step. The reworked BGA's reflow temperatures are not measured since thermocouple cannot be installed meaning the reflow results can only be verified by inspection. Figure 3 below gives a typical operational hot air BGA rework configuration.

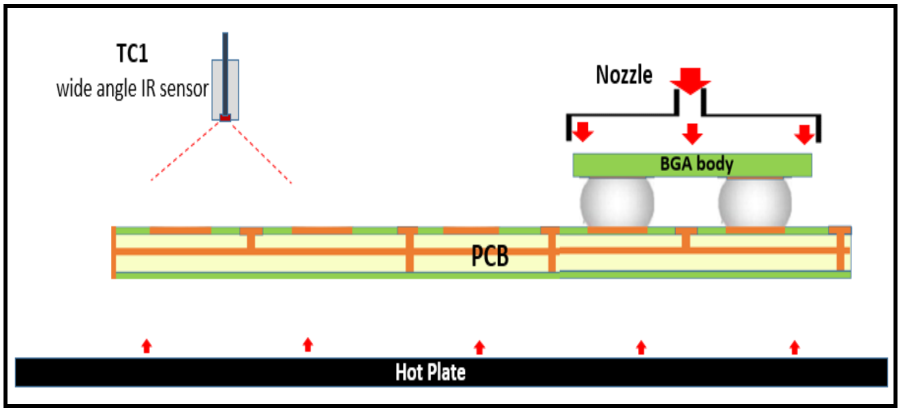


Figure 3 - Typical operational hot air BGA rework configuration

Figure 4 below charts a typical hot air rework profile for a tin-lead application. The temperatures of the hot air nozzle and TC1 sensor shown relative to time are consistent with the readings at the profile development. However, note that compared to Figure 2 we don't now have a thermocouple monitoring the BGA's actual temperatures directly, trusting that our generated profile chart will be repeatable for this application.

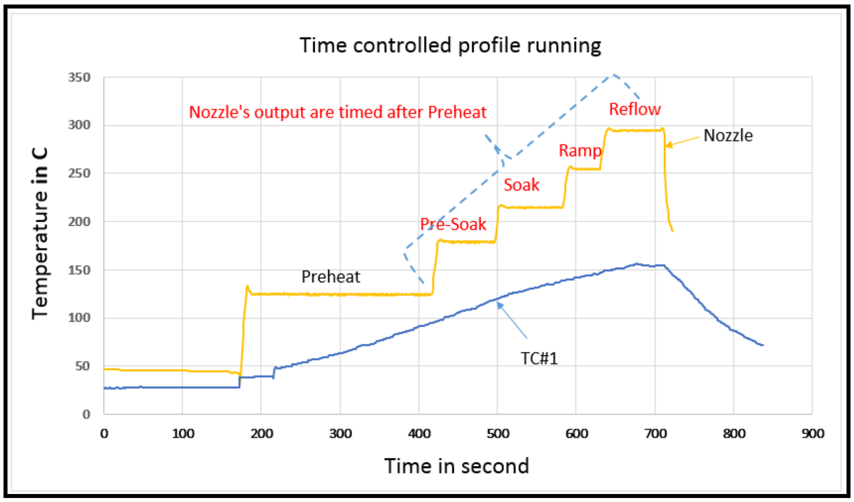


Figure 4 - Nozzle and TC1 profiles during typical hot air real BGA rework

However, we have other unmonitored factors (inputs) not represented in these charts which may influence the resultant temperatures seen by the solderball. Such factors that are commonly considered constants can in reality experience variability.

Factors with examples that influence variability of temperatures seen by the solderball:

- Environment air temperature/flow
    - From expected variances such as change in seasons or existing building ventilation to unexpected such as a fire drill keeping the door open for long periods or heavy equipment moving past the rework area creating a draft
- Machine variation/maintenance
    - The profile may have been generated just before or just after a preventive maintenance that altered the readings taken during profile generation/verification relative to current state
    - TC1's position and height are challenging to keep constant resulting in variability in readings
- Human error opportunities
    - Use of incorrect profile from high number of available choices

The result of all this is that our device could be either under reflowed or over reflowed. The newly generated profile was good for yesterday's job but is not good for today. Also, the profile is good for this specified device but not good for other BGA devices on the same card. The profile is optimized for one machine but may not provide acceptable results on other machines, even of the same model. Therefore, we are struggling not only to generate many profiles for different devices and different cards but also to adjust them from machine to machine and from day to day. Even then, we are still not fully comfortable with each reflow result. Each AirVac reflow result is affected by variations and conditions of board, machine, and operation environment, so it's very possible to produce unexpected results. One approach to produce more consistent results is a Temperature Dependent Live Feedback Process for each operational rework to replace the traditional time dependent profile.

A second challenge is in the capability to properly generate the initial profile, particularly to embed thermocouples in BGA solder balls when preparing the profile card. According to IPC-7095D and most of today's industry recommendations, we need to drill a hole from the assembled PCB's side opposite the affected BGA through the PCB, and targeted to terminate just into the ball. We then need to thread the thermocouple through the drilled hole and secure against the PCB creating contact with the BGA ball. Figure 5 below shows this in the target condition, but this is difficult to achieve particularly for today's fine pitch BGAs with small ball diameter.

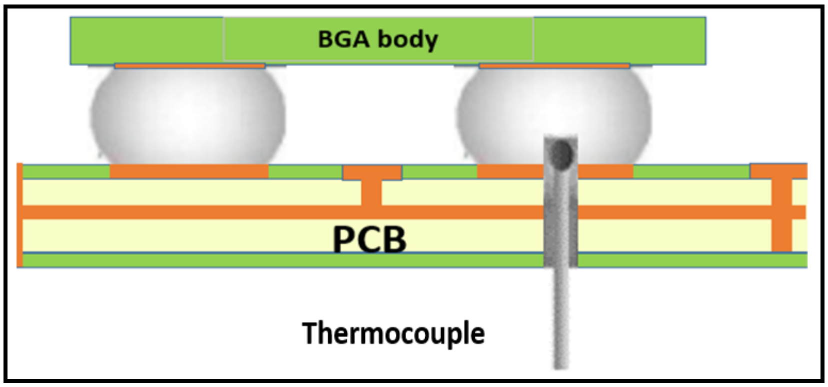


Figure 5 - Embed thermocouple in BGA ball

a. If the wire does not touch the ball, as in Figure 6 image (a), the thermocouple's temperature reading will be lower than the ball, and the generated profile might lead to over reflow during real rework.
b. If the wire does not touch the ball, as in Figure 6 image (b), the thermocouple's temperature reading may be higher than the ball, and the generated profile might lead to under reflow during real rework.

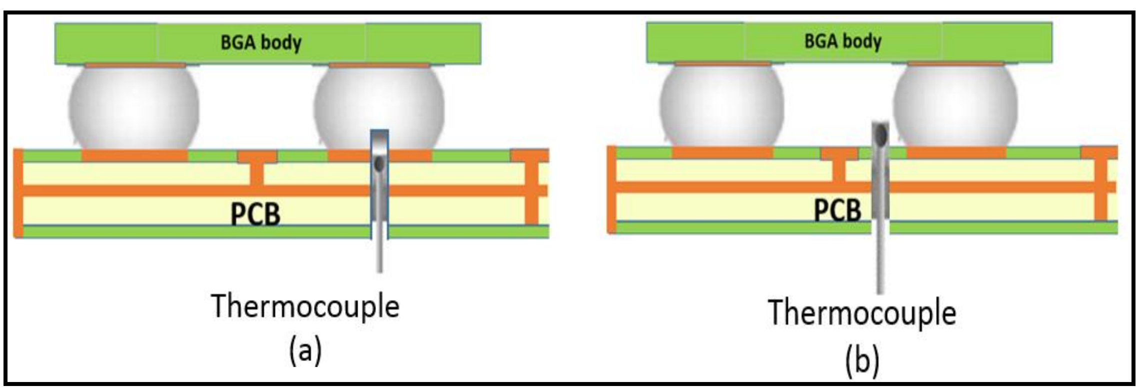


Figure 6 - Embedded thermocouple not in contact with BGA ball

Discussion of Methodology

In today's industry recommendation, all focus is on the reflow temperature of the BGA ball. Let us review a typical heat transfer path during reflow, the main heating is transferred from top nozzle hot air to BGA body, to BGA ball, then to PCB solder pad. If we measure solder ball disconnected from PCB (as is the case when the pad is drilled out to enable TC wire attach), we are measuring temperatures of BGA ball which will be only a small percentage of thermal mass of PCB underneath. In real circuit application, many PCB BGA pads are directly linked to copper floods at either the same PCB layer or other layers by vias. In such application, an obvious thermal gradient will exist between the ball and the PCB pad particularly if PCB underside heating is insufficient. Figure 7 illustrates the thermal gradient between BGA ball and PCB pad. Therefore, even if a solder ball reached reflow temperature under monitoring when disconnected from PCB, it does not mean the ball can solder properly to PCB. In order to have ideal solder joints both ball and PCB solder pad should reach the reflow temperature. In this paper, we are not going to discuss the solutions to reduce the thermal gradient between bulk of PCB and rework area, but studies are available which detail thermal relief and increase pre-heating on the PCB as solutions already.

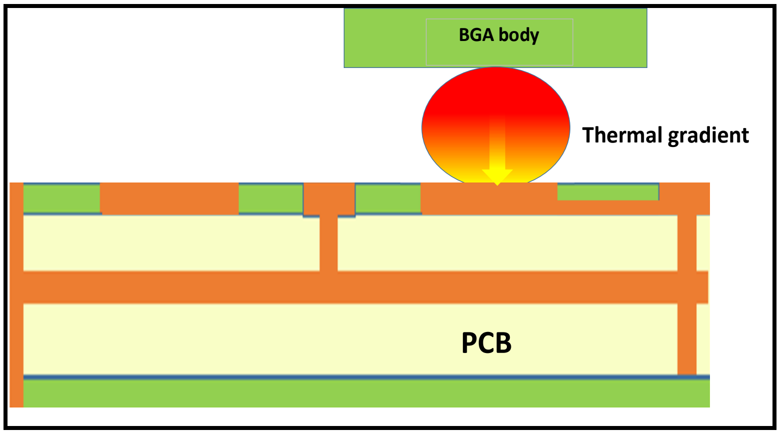


Figure 7 - Thermal gradient between BGA ball and PCB pad

Now we move the focus of reflow temperature to the joint interface between BGA ball and PCB solder pad. If the PCB solder pad meets the reflow temperatures, the BGA ball and the PCB pad will have a joint with good solder wetting. Figure 8 (a) to (b) illustrates the new focus of reflow temperature between BGA ball and PCB pad.

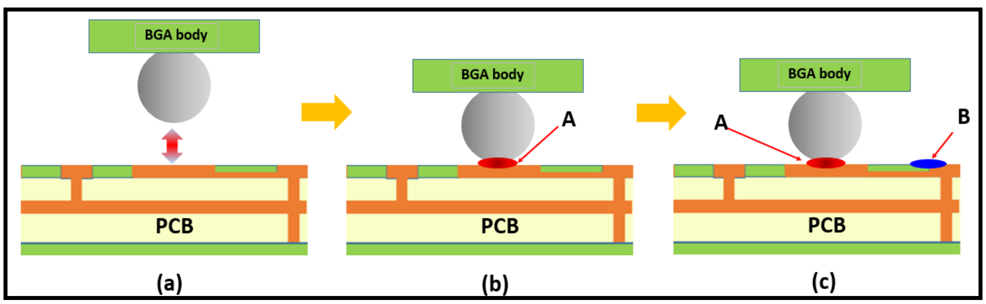


Figure 8 - Focus of reflow temperature between BGA ball and PCB pad

In Figure 8, we introduce a spot B that is on the PCB surface and adjacent to the BGA ball solder joint A. Do A and B in Figure 8 have equivalent temperatures? Yes, we have shown we can maintain A and B's temperatures to less than 5C variations under certain conditions in our regular hot air BGA rework systems: the top hot air nozzle sizes are about 2mm wider than the BGA device's dimensions and the heating from the bottom hot plate are sufficient to achieve this. The following portion of this paper will detail our experiments and analysis performed to prove this.

We will note here that this temperature equivalence between A and B in Figure 8 is only good for the top hot air process, and the conclusion is not applicable if the top heating is infrared (IR) heater.

Experimental Proof of Concept

Figure 9 below illustrates our experiment #1 with top mounted and back drilled mounted thermocouple. The experimental PCB dimension is 234x160 x 2.4mm with 22 layers, the BGA size is 37.5x37.5mm with 1667 balls (lead free), and the hot air nozzle size is 40x40mm. Four thermocouples are assembled: #2 and #3 TCs are installed through drilled PCB holes to touch BGA balls; the #5 and #6 TCs are installed on top PCB surface; #5 is adjacent to #3 ball and #6 is adjacent to #2 ball. A classic time dependent lead free reflow profile was used to capture data.

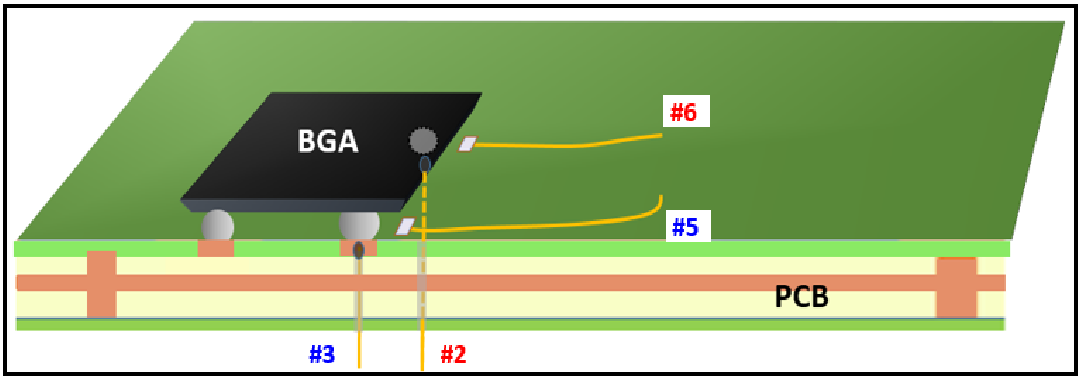


Figure 9 - Illustration of top adjacent and back drilled mount 4 thermocouples

Table 1 and Figure 10 provide the captured profile (lead free), peak temperatures and time above 217C comparisons of the four different mounted thermocouples.

Table 1 - Experiment #1 Temperature comparisons between top mount and back drilled mount thermocouples

Thermocouples	Mount type	Peak Temp. in C	Time above 217C in Second
TC #2	back drilled	238	109
TC#3	back drilled	239	113
TC #5	Top adjacent	236	99
TC #6	Top adjacent	238	110

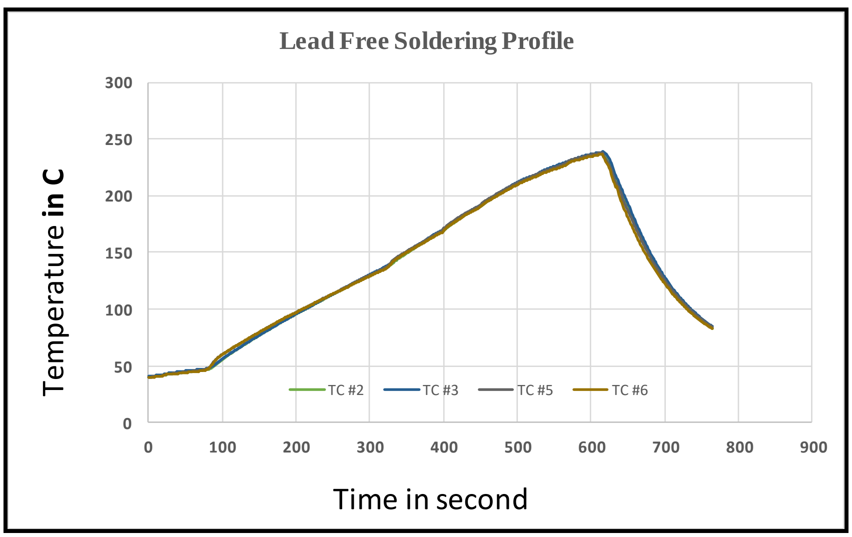


Figure 10 - Experiment #1 Captured lead-free solder profile for four thermocouples

The above data shows that the top mounted and adjacent to BGA ball's thermocouples have equivalent temperatures to the back drilled mounted thermocouples. Similar experiments were carried out on different PCB, BGA devices and AirVac machines, and captured profile data continually supported that the temperatures in Figure 8 location A and B are equivalent in hot air reflow process. Table 2 summarizes parameters and results of these experiments.

Table 2 - Multiple trials showing temperature delta between BGA pad and neighboring spot on PCB

Profile board #	AirVac machine #	Solder type	Peak Temperature Delta +/- in C	Adjacent B Peak Temperature	BGA pad A Peak Temperature	PCB size in mm²	PCB thickness in mm	PCB layers	BGA size in mm²	BGA balls
#1 a	M1	LF	**-3**	236	239	160x234	2.4	22	37.5x37.5	1667
#1 b	M1	LF	**0**	238	238	160x234	2.4	22	37.5x37.5	1667
#2	M1	LF	**-2**	233	235	120x125	1.6	14	26x26	672
#2	M2	LF	**1**	233	232	120x125	1.6	14	26x26	672
#2	M3	LF	**2**	233	231	120x125	1.6	14	26x26	672
#3	M1	LF	**1**	235	234	160x234	2.5	20	26x26	676
#3	M2	LF	**2**	234	232	160x234	2.5	20	26x26	676
#3	M3	LF	**1**	234	233	160x234	2.5	20	26x26	676
#4	M1	Pb	**1**	210	209	155x230	2.64	22	33x33	844
#5	M3	Pb	**4**	212	208	160x234	3.43	32	57x14	400
#6*	M1	Pb	**2**	213	211	160x234	1.68	18	29x29	483
#6*	M2	Pb	**4**	212	208	160x234	1.68	18	29x29	483
#6*	M3	Pb	**3**	211	208	160x234	1.68	18	29x29	483
#7*	M1	Pb	**-3**	210	213	160x234	2.03	16	25x25	360
#7*	M2	Pb	**4**	210	206	160x234	2.03	16	25x25	360
#7*	M3	Pb	**0**	210	210	160x234	2.03	16	25x25	360
#8*	M1	Pb	**-2**	218	220	31x142	1.57	12	20x20	324
#8*	M2	Pb	**0**	216	216	31x142	1.57	12	20x20	324
#8*	M3	Pb	**1**	217	216	31x142	1.57	12	20x20	324

Analytical Proof of Concept

We next used an analytical approach in an attempt to support what we have seen through experimental trials. Using standard thermal simulation software and the readings seen in our experimental trials, we tried to calculate the expected thermal gradient across the PCB from the reworked part spot “A” to the temperature-monitored spot “B”. We used a simple scenario where we applied the TC1 wide-angle temperature reading to the mass of PCB 2.5” away from BGA under rework and iteratively applied a set temperature to the entire BGA area being reworked. The TC1 value used was the actual temperature of board seen during our experimental trials, which were known to be representative of temperature profiles that would be used in live production. Thermal conductivity of the PCB was based on copper/FR4 content and values were set as through-plane (z) conductivity of 0.37 W/mK, and an in-plane (x/y of outer layer) conductivity of 74.8 W/mK. Knowing from repeated experiments that the corner pins are the coolest area during a standard rework process it was chosen to set the bulk of BGA to be all one temperature. The simulations were repeated with differing BGA temperature values until simulation showed the experimentally derived trigger temperature at our monitored spot “B”. This simulation shown in Figure 11 resulted in a maximum temperature delta of 4 degrees C at the SnPb profile highest step of 210 C, which is the trigger to halt the reflow stage of profile. We attribute the fact that this delta is larger than experimentally observed to the simulation software only accounting for the conduction of heat across the PCB, and not accounting for any convective heat transfer to/from the surrounding air. In real application, some convective heat transfer is expected which explains why the experimental delta is less than the simulation results. The results of both experimental trials and analysis were enough to support moving to the next step of the process, which was to find a method to incorporate this into rework on populated circuit card assemblies (CCAs) and monitoring the results.

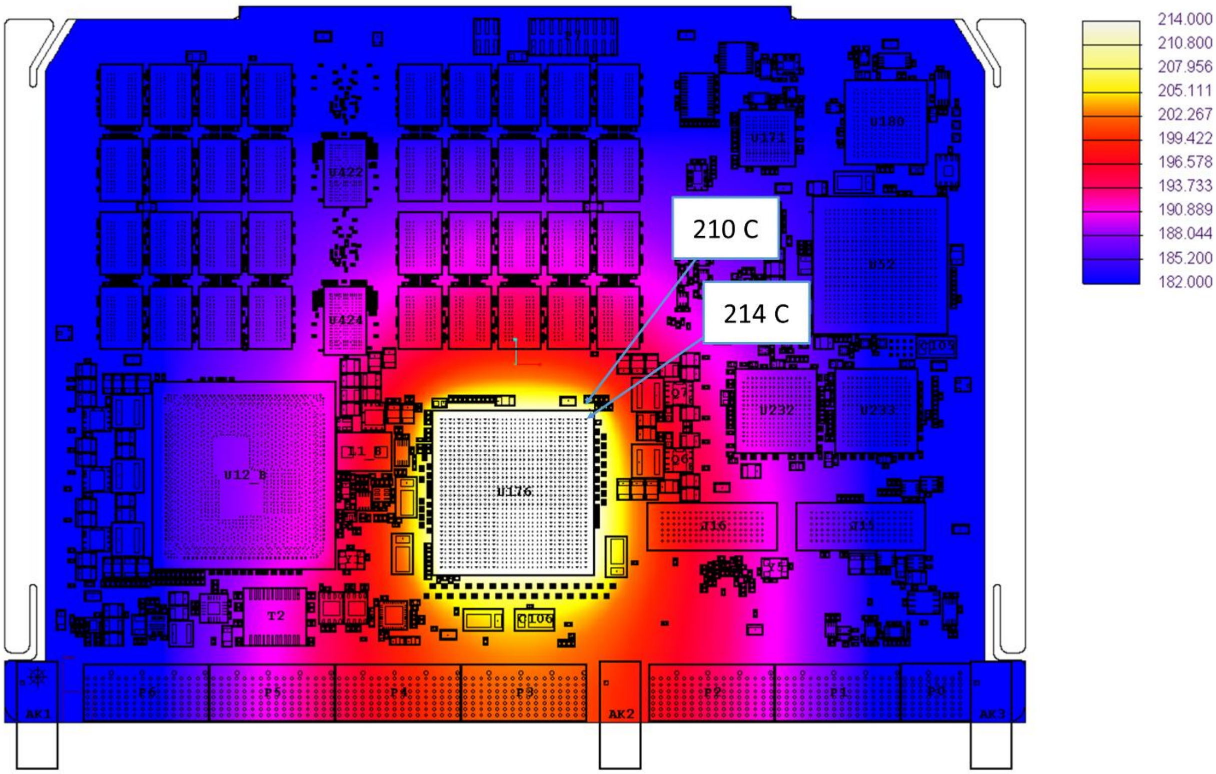


Figure 11 - Thermal Modeling of PCB Thermal conductivity under rework simulation

Development of a Solution

Now that we have proven the spot “B” in Figure 8 can be considered equivalent to BGA solder joint spot “A” temperature dynamically during whole reflow process. We can also see access for live temperature monitoring at this location “B” is possible, therefore a natural progression would be to consider building a temperature dependent live feedback reflow profile through the spot “B”.

Initially, we assembled a standard thermocouple wire sensor TC2 at spot “B” as shown in Figure 12 and built temperature dependent reflow profile from this configuration. The TC1 with wide-angle IR sensor measures was still used to monitor PCB’s average temperature, and trigger profile step from Preheat to Pre-Soak. Our change was that for the following steps of Pre-Soak, Soak, Ramp and Reflow, the nozzle’s outputs were now triggered by reading of TC2.

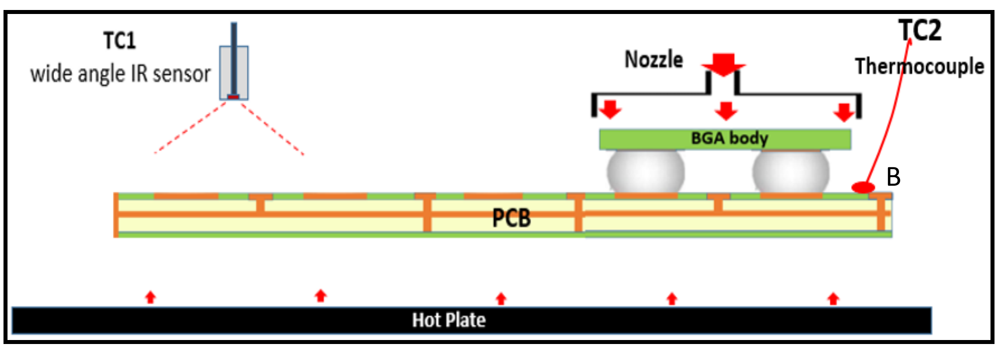


Figure 12 - Thermocouple wire TC2 temperature dependent profile configuration

Shortly, we found a commercial universal temperature IR sensor with laser aiming. The laser’s operation, including measurement temperature range and spectral range 8-14um, was ideal for solder reflow temperatures and PCB material. A small focused laser spot size of 2mm allowed for the proximity needed including for the densely populated PCBs most challenging for the standard methodology. The laser’s working distance of 200mm was a good fit for our existing machine set-up. Figure 13 illustrates a typical laser IR TC2 temperature dependent profile configuration.

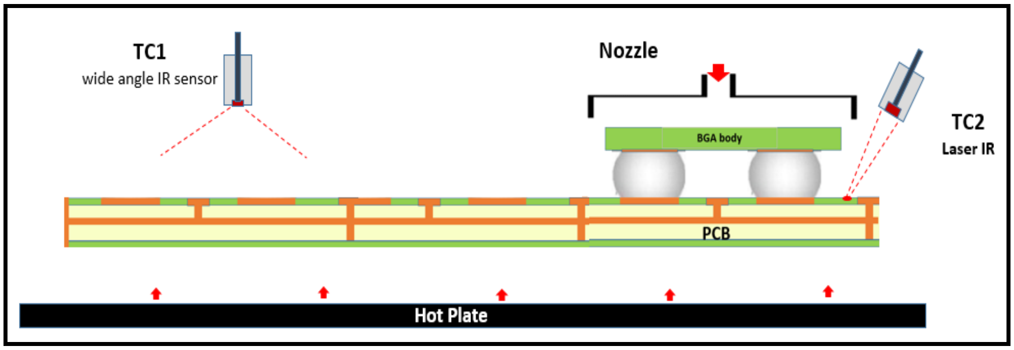


Figure 13 Laser IR TC2 temperature dependent profile configuration

It is important to verify and correct laser IR sensor's temperature output with standard K-type (or others) thermocouple output before application. Figure 14 illustrates laser IR verification configuration. There are three AirVac machines in our manufacturing floor and each is equipped with one laser IR sensor, and we have set a daily verification requirement for each.

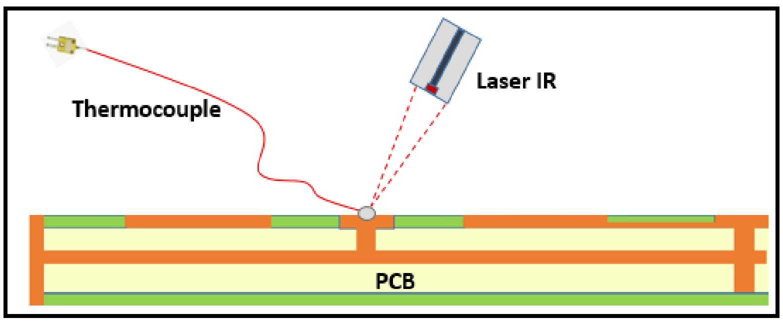
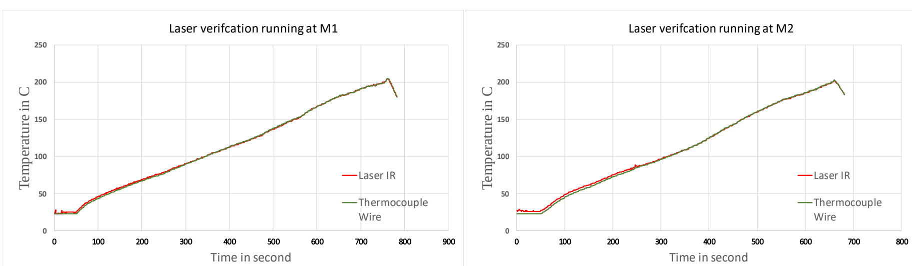
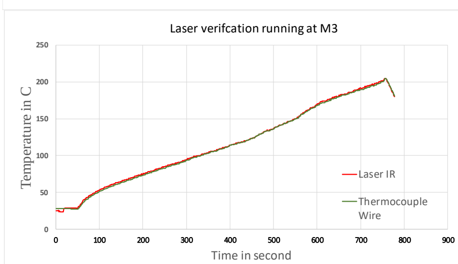


Figure 14 - Laser IR verification

Figure 15 gives typical three AirVac machines with each laser IR sensor verification profiles and their verification data at 200C for 12 months.





Three Laser IR sensors 12 months 200C verification data
CPKs are with +/- 5C upper and lower limits

Laser IR #	Machine #	Stand dev	Mean	CPK
#1	M1	1.1	198.5	1.51
#2	M2	1.2	200	1.43
#3	M3	1.1	198.9	1.52

Figure 15 - Three Laser IR sensors typical verification profile and their 12months 200C data and CPKs

Comparative studies of Process Capability

We next undertook a plan to show via repeated trials that results from this process are more resistant to common variables seen in a production environment than the standard accepted practice. These variables are chosen to be reflective of the realities noted in the introduction and existing challenges section of this paper. For these experiments, we developed and confirmed a time-dependent reflow profile using existing best practices of verifying good placement of thermocouple within BGA ball and repeating profile in initial set-up to demonstrate repeatability. This profile was saved and considered representative of a time-controlled profile that could be used for production practice. The temperature-dependent profile was developed in the manner described in “Development of a Solution” section of this paper and these 2 profiles were ran on our sample card in the differing scenarios recording the key reflow parameters of Peak Temperature, and Time Above Liquidus (TAL).

For all charts:

- Solid line represents Temperature-dependent profile results.
- Dashed line represents Time-dependent profile results.
- Chart1, Chart2: Colours in legend indicate machine being charted
- Chart3, Chart4: Dark represents BGA location 1, and Gray represent BGA location 2

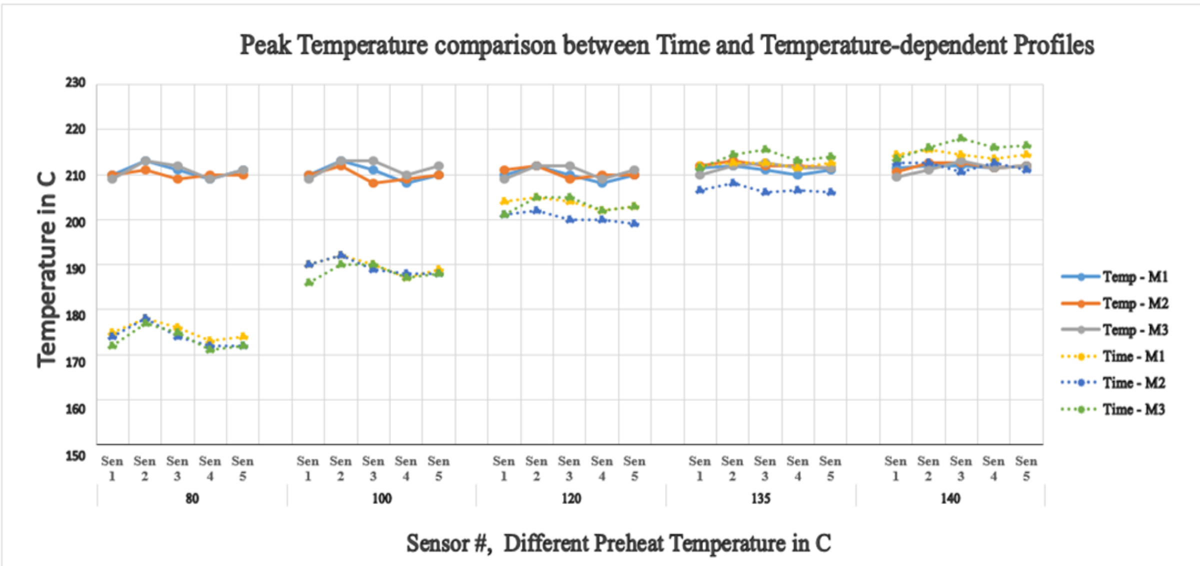


Chart 1 - Measuring Peak Temp with Varying Preheat Temps across different Machines with same Board Location

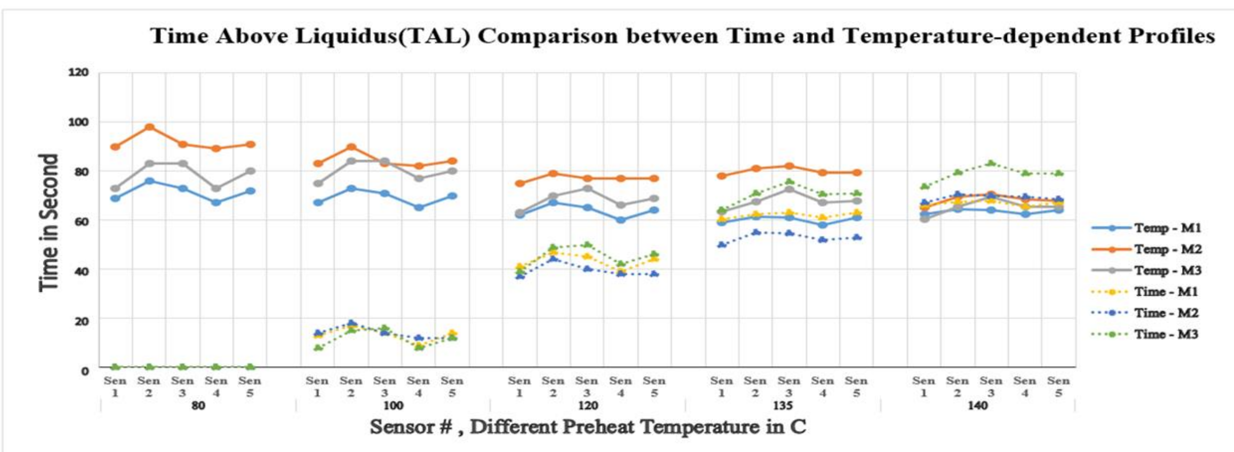


Chart 2 - Measuring TAL with Varying Preheat Temps across different Machines with same Board Location

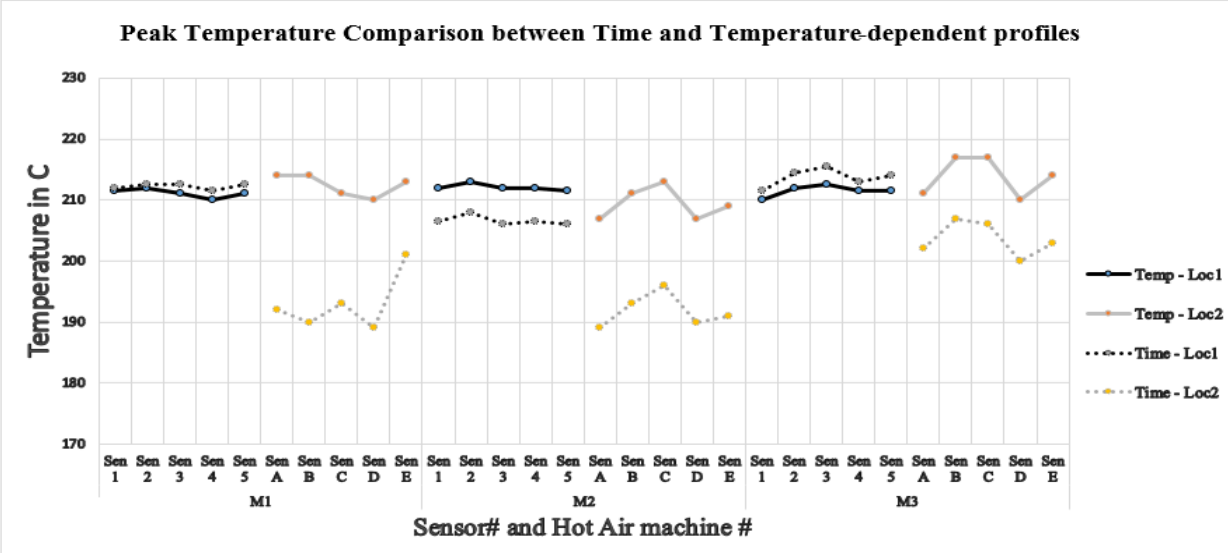


Chart 3 - Measuring Peak Temp with Preheat set at 135C; Variables of Machine and Board Location

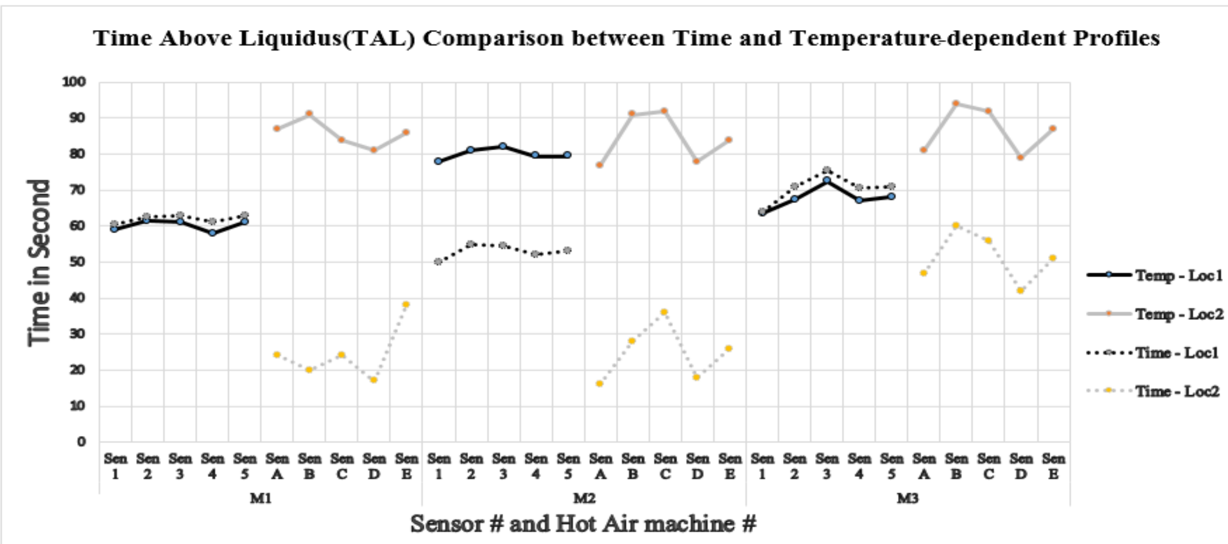


Chart 4 - Measuring TAL with Preheat set at 135C; Variables of Machine and Board Location

Charts 1, 2 show the TC1 Preheat trigger temperature used is critical in the time-dependent profiles while the temperature-dependent process is more resistant to variation. In charts 3, 4 we chose the most successful preheat trigger value of 135C and evaluated performance of Peak Temperature and TAL under practical real-life variables. Those being using the same profile on multiple machines and using the same profile for different locations on same board. In each scenario, the temperature-dependent profile is seen to be within acceptable range for the key reflow parameters while the classic time-dependent profile leaves an opportunity to be outside the range. These charts clearly show the expected improved repeatability using the temperature-dependent profile.

Conclusion and Discussion

We have shown that using a live feedback PCB temperature monitoring system to drive the parameters of a hot air reflow process, results are more consistent and there is better control over common practical variables that occur within the classic time-dependent methodology of hot air rework. The temperature values monitored are shown both analytically and experimentally to be sufficiently close and consistent to be relied upon to keep actual solder ball temperatures during the rework cycle within acceptable range for key criteria. From a practical viewpoint and proven within this paper experimentally it is clear that using a temperature-dependent profile during the BGA hot air rework process is less impacted by common production variables such as use of different machines, sub-optimal profiles generated with improperly configured samples, re-use of profile developed at a different PCB location, and TC1 Preheat trigger changing.

It has helped us reduced our total profile numbers from more than two thousand to around 50, and reduced the second rework rate significantly.

Acknowledgements
The author would like to acknowledge assistance of Anghere Tang, Cuifang Huang, Phalla Tep, and Vui Nguyen for their assistance in conducting simulations and trials referred to within this paper.

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