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PRACTICES TO ASSURE CONSISTENT AUTOMATED HOT GAS REWORK

Mitchell Ferrill
IBM Corporation
Endicott, NY, USA
ferrill@us.ibm.com

Musheer Ahmed
Celestica Inc.
Toronto, ON, Canada
musheera@celestica.com

ABSTRACT

Hot gas rework is a critical process for the recovery of high priced electronic card assemblies which need defects repaired or components upgraded. It is a requirement that the rework process produce quality and reliability levels that are equivalent to original assemblies. Much time and attention is generally spent establishing a program, or recipe, for reworking a particular device location on a complex assembly. This is normally accomplished by inserting thermocouples into the component solder joints in order to measure the temperature experienced during the process. Having the correct recipe is critical for achieving the proper metallurgical interaction, especially for mixed metallurgy (Pb free device attached to a card assembly with SnPb paste) and Pb free assembly. Most automated hot gas rework tools have a trigger (or tool control) thermocouple which is used to initiate the rework program. Once this thermocouple reaches a specific temperature a series of timed steps begin. Care must be taken to locate this thermocouple in nearly the same location as that used to establish the recipe with the thermocoupled profile card. It is also critical that this trigger thermocouple be in intimate and consistent contact with the PCB (Printed Circuit Board) surface. If proper attention to these details is not taken, then the resultant peak temperatures actually reached on the product may be much different than expected. This can result in poor quality solder joints that pose a reliability exposure. This paper discusses some common practices observed at various CMs (Contract Manufacturers) that can lead to inconsistency in rework. It also discusses practices and techniques that will reduce and/or eliminate the potential inconsistency.

Key words: Hot gas rework, BGA

INTRODUCTION

Hot gas rework has been practiced successfully for many years and continues to be a critical and integral part of any electronic assembly manufacturer's process. Photos of some hot gas tools available on the market are shown in Figures 1 and 12.

Figure 1. Automated Hot Gas Rework Tool

As with any process, long term use and success can lead to a view that the operation is routine. As a result, some level of casualness may develop resulting in a lack of attention to detail.

Figure 2 shows an example of a hot gas rework profile for a ball grid array (BGA) device on a complex electronic card assembly.

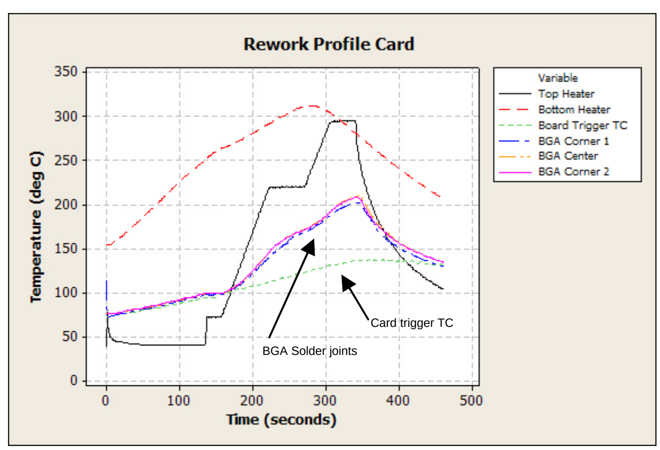

Figure 2. Profile Card Temperature Plot

It is common for hot gas rework tools to provide not only a graph which tracks multiple thermocouples, but also a summary table containing data for several rework parameters. One such output table is shown in Figure 3.

	A	B	Slope	Min	Max	Liq
top htr ☑	66	104	0.1	40	295	164
btm htr ☑	155	207	0.1	154	312	414
Ext Brd ☑	73	133	0.1	73	138	0
Corner1 ☑	74	130	0.1	73	202	61
Ctr ☑	77	135	0.1	76	210	70
Corner3 ☑	76	135	0.1	76	208	69

Figure 3. Rework Tool Output Table

The tool has two heating sources. The bottom heater, which is basically a hot plate that provides the initial board preheat, and the top heater where the hot gas is introduced and causes the solder to reflow. A trigger thermocouple, which the rework tool software labels as "Ext Brd", is attached to the PCB assembly some distance away (2.5 to 5 cm for example) from the component being reworked. As seen in Figure 2, the program for rework of this particular device initiates a series of timed top heater heating steps once the trigger thermocouple reaches 95®C. At the end of each of the timed steps, a new temperature set point is defined. Once the timed steps commence, the trigger thermocouple provides no further input or influence on the remainder of the rework program. Upon dialing in the thermal profile, the control program is stored on the tool and the process control documentation is updated to define unique requirements for the specific device being reworked on the card assembly.

After defining the rework program and completing the process documentation and training, rework is then typically allowed to commence on customer shippable product. The common industry sequence of events for this rework would typically be as follows:

1. Load the assembly to be reworked into the tool and attach the trigger thermocouple.
2. Select the rework program and start it. Operators generally watch the start to confirm everything is running acceptably. After the start though, it is very common for the operators to walk away from the tool and do some other work while the rework program is running. They may or may not come back a time or two to check on status.
3. Confirm the rework program has completed successfully.
4. Visually inspect the device that was reworked. This is often done with a scope and a hand held mirror.
5. Complete data logging and send part to test.

The industry generally fails to take full advantage of the rework tool program outputs (i.e. – the graph and output table). Because the card no longer has thermocouples in the solder joints, these tool outputs are not considered useful, other than to confirm that the tool:

1. Has completed the program steps
2. Went through the timed steps and that the temperature changed.

There is one very useful piece of data that is generally overlooked, and that is the maximum value reached by the trigger thermocouple.

Figure 4 shows the tool output data for the rework of a functional, customer shippable product card. The card assembly and rework program were the same as those discussed earlier in this section. The "Corner1", "Ctr", and "Corner3" values are missing in Figure 4 versus Figure 3 as these are the thermocouples imbedded in the solder joints and are not present on functional product.

	A	B	Slope	Min	Max	Liq
top htr ☑	55	73	0.0	39	295	140
btm htr ☑	100	170	0.1	100	303	401
Ext Brd ☑	57	113	0.1	56	184	5

Figure 4. Rework Tool Output Table for Product Card

This data indicates that the trigger thermocouple reached a peak temperature of 184®C, which was 46®C higher than the 138®C measured when the rework profile was established (Figure 3). This result indicates the following:

1. This product profile does not match the original setup, otherwise the peak temperature reached by the trigger thermocouple should have been near 138®C
2. The trigger thermocouple, which is located away from the part being reworked reached 184®C, indicating that the adjacent components went into reflow, which is not a desirable condition

The process controls should cause an immediate flag to be raised, but this type of control is not generally used in the industry. This paper discusses techniques and controls that provide the best opportunity for an acceptable and repeatable rework process and minimize the opportunity for defects related to improper reflow.

FACTORS THAT CAN INFLUENCE PROFILE CONSISTENCY

The following elements can influence the rework profile consistency and should be an area of focus when setting up and controlling / monitoring any hot gas rework process.

1. Trigger thermocouple placement
2. Trigger thermocouple attach method
3. PCB assembly support method/locations in rework tool
4. PCB assembly orientation in rework tool
5. Initial profiling methodology

Each of these items will be discussed in detail and recommended actions / solutions are included.

Trigger Thermocouple Placement

Overview: Careful and consistent placement of the trigger thermocouple is a requirement to assure a consistent rework profile. Attention should be made to card features in the area where the thermocouple is placed. Placement on PTHs (Plated Through Holes), wiring features such as ground/power buses, wide conductors, etc. such as those shown in Figures 5 and 6 should generally be avoided. This is because achieving a repeatable result in these areas is difficult. Open areas are best.

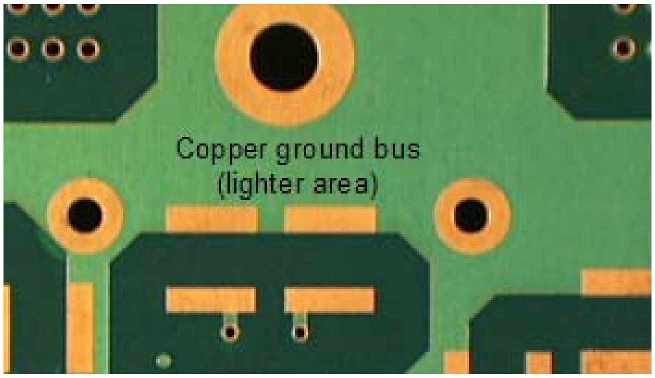

Figure 5. Large Cu Shape on PCB Surface

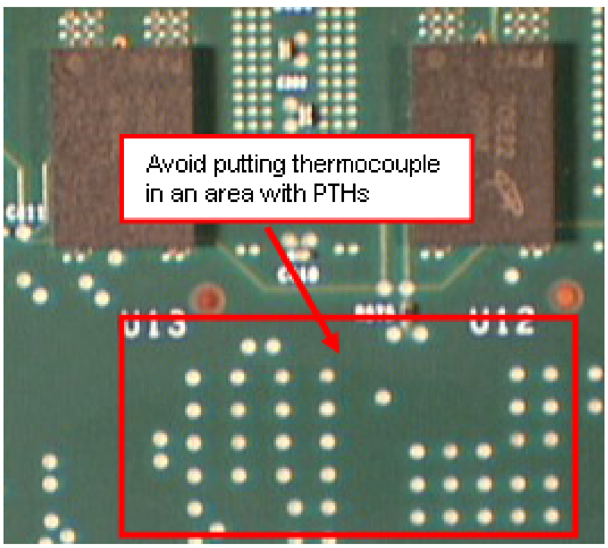

Figure 6. Avoid Areas with PTHs

If for example, the trigger thermocouple were to be placed in the area in the red box, shown in Figure 6, it would be easy for the operator to be either on a PTH or on the PCB solder mask (green area). Each would transfer heat differently and thus have an impact on the trigger thermocouple (temperature, heating rate, etc). This is why it is more important to establish a defined placement location and reflect this in the process instructions. Once established, multiple profile runs should be performed to confirm repeatability.

Example: The following profile shows an example of why it is critical to define a specific trigger thermocouple location. An initial profile was run with the trigger thermocouple in the location shown (See Figure 7).

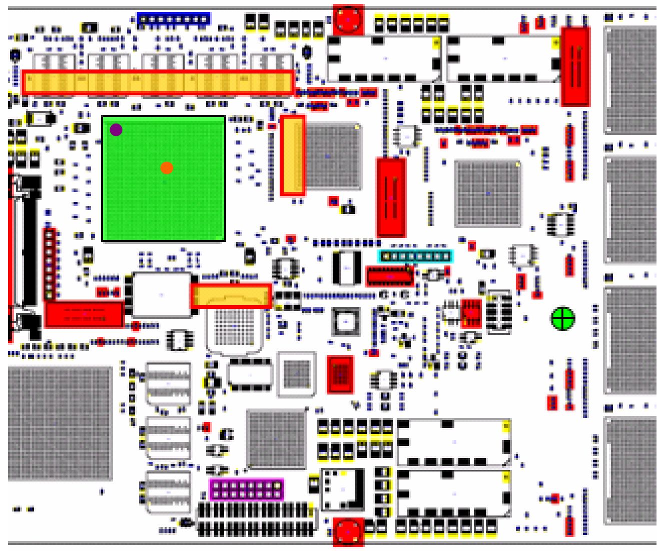

Figure 7. Profile Run 1

The trigger thermocouple location is shown by the green circle with the cross. The profile parameters that resulted are shown in Figure 8.

- Corner joint temperature = 203 deg C for 60 seconds
- Center joint temperature = 211 deg C for 85 seconds
- TTC location 'A' & the Peak temperature recorded during thermal profiling is 148 deg C

Figure 8. Profile Run 1 Result

All the solder joints were above the desired minimum of 200®C and the trigger TC (thermocouple) reached a peak of 148®C. The profile was rerun with the trigger thermocouple in a slightly different location as shown in Figure 9. This location is one that could easily be chosen by an operator and considered equivalent to the location initially used for the first profile (Run 1).

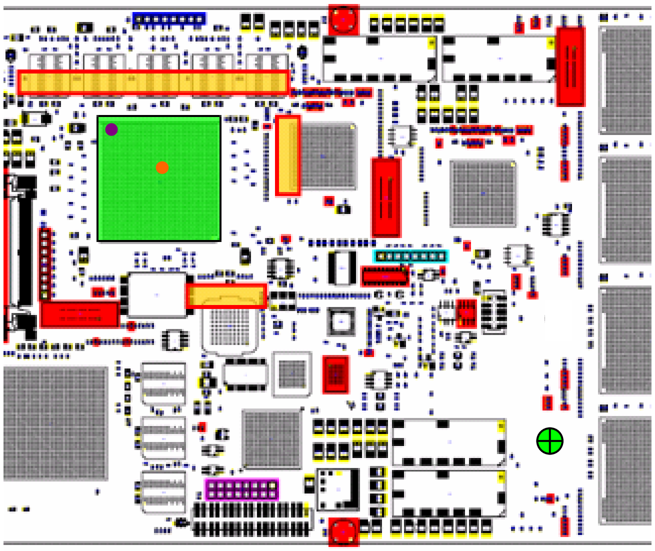

Figure 9. Profile Run 2

The resultant profile parameters are shown in Figure 10.

- Corner joint temperature = 198 deg C for 38 seconds
- Center joint temperature = 208 deg C for 68 seconds
- TTC location 'A' & the Peak temperature recorded during thermal profiling is 141 deg C

Figure 10. Profile Run 2 Results

The new trigger thermocouple location has resulted in the corner solder joint temperature dropping below the desired minimum of 200®C and also note that the peak trigger thermocouple temperature is indicative that something has changed (change from 148®C to 141®C).

Solutions: There are two primary solutions that can be employed to assure that the trigger thermocouple location is repeated for each and every rework.

1. Provide a schematic or photo in the rework process instructions – Something similar to that shown in Figure 9 has been shown to be adequate. In this scenario though, operators need to be educated as to the importance of the trigger thermocouple location and why attention to this detail is critical.
2. Create a template – A template provides a very direct and easy way to locate the trigger thermocouple (see Figure 11). The template is laid over the part in order to locate the trigger thermocouple location and then the template is removed. These templates are simple to make and not costly.

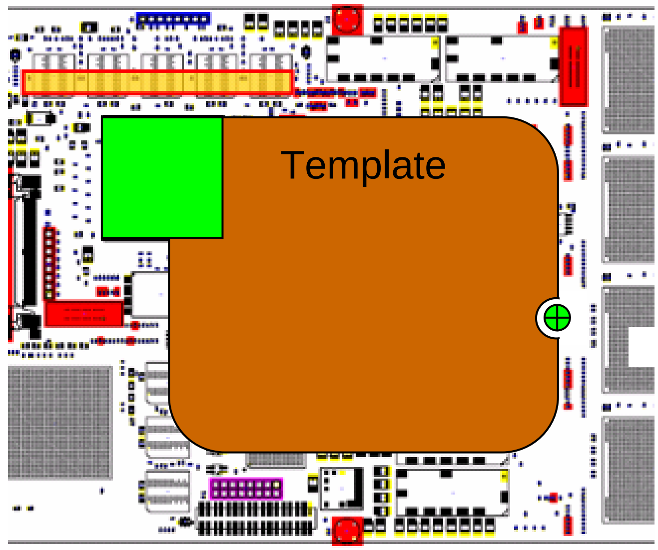

Figure 11. Template Example

Trigger Thermocouple Attach Method

Overview: In order for the trigger thermocouple to provide an accurate temperature measurement, it must be in good contact with the product surface. If the thermocouple is not in good contact, then the trigger thermocouple may respond differently than desired. For example, if the thermocouple has an air gap between it and the product surface, the thermocouple may indicate that it has reached the desired trigger point temperature before the product has reached the desired temperature. This scenario would cause the timed steps to start prematurely. This can result in solder peak temperatures that are well below those desired and this can lead to inadequately reflowed solder joints and improper metallurgical structures. After observing a few rework CMs, a common practice is noted at many of the locations. This practice is to attach the trigger thermocouple to the board using a piece of polyimide tape. After completing the rework, the thermocouple and tape are removed and stuck to the upper portion of the tool (see Figure 12).

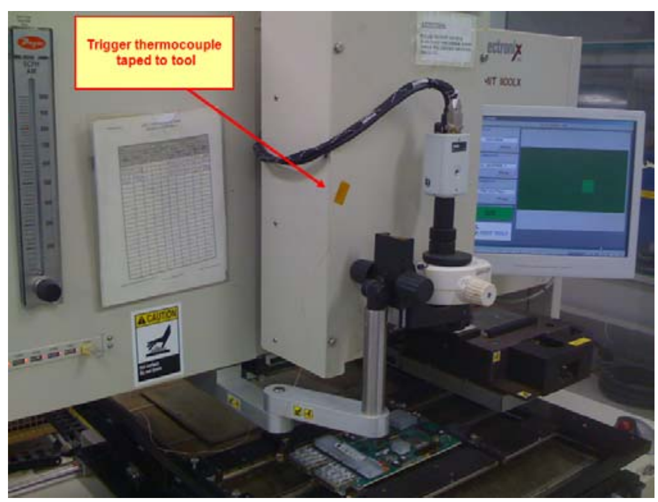

Figure 12. Trigger TC stuck to front of machine

This same piece of polyimide tape is used repeatedly until the operator determines it no longer has adequate adhesion, which is generally many reuses.

Figure 13 shows a Type "T" thermocouple attached to a PCB using polyimide tape.

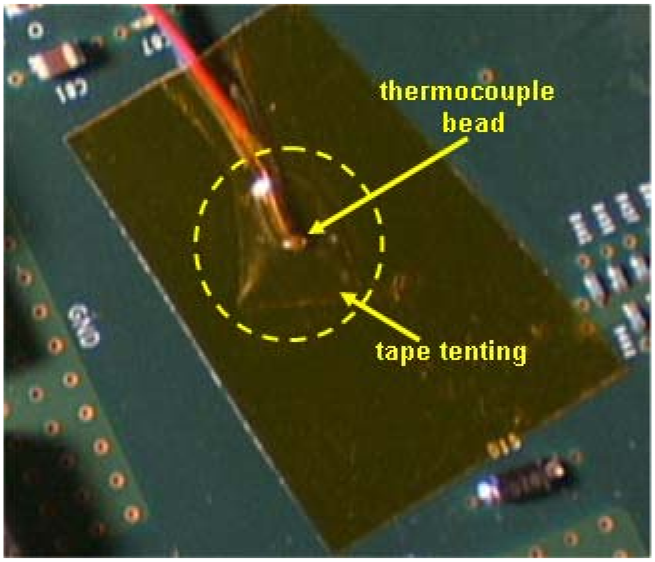

Figure 13. Polyimide Taped Thermocouple on PCB

The tape tents around the thermocouple bead (or tip) and does not adhere to the PCB at all in this area. Logically, the smaller the non-adhered area the greater the downward force will be applied to the bead, and thus the better the thermocouple contact to the PCB surface. It should be noted that the amount of tape shown in Figure 13 is generous compared to the amount that was observed being used at some CMs. A smaller amount of tape will make it more difficult to keep the thermocouple bead in contact with the PCB. To further demonstrate this, some simple experiments were run. A 4-wire measurement was done of a simulated thermocouple bead against a copper plate. This is shown in Figure 14.

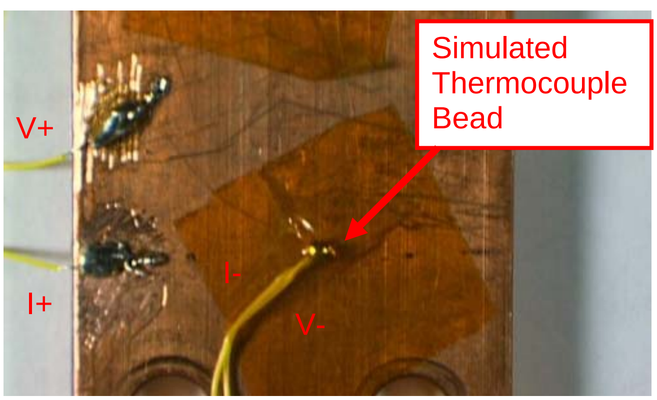

Figure 14. 4-wire Measurement Setup

When a new piece of polyimide tape was used, the electrical reading was low and relatively stable, indicating good contact between the simulated thermocouple bead and the copper plate. With multiple uses though, the resistance increased and eventually became an open, clearly indicating the thermocouple was no longer in contact with the surface. The outer edges of the tape were still adhering to the copper plate, so an operator would likely be unaware of this situation, if this were to occur on a PCB. The amount of tape reuse that led to an open varied greatly.

This same experiment was repeated using a metal tape.

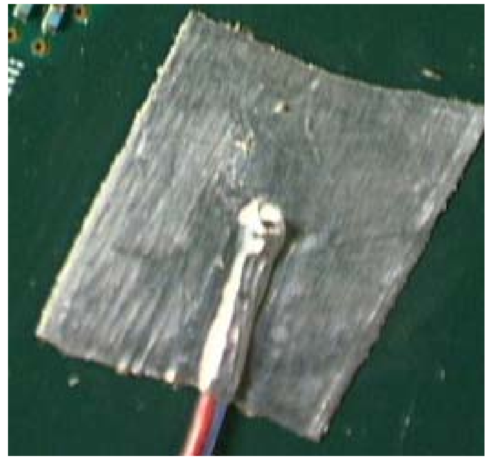

Figure 15. Metal tape over thermocouple

As seen from Figure 15, a metal tape conforms around the thermocouple bead and assures that it is held firmly down against the PCB surface. When the 4-wire measurements were done, the electrical measurement was low, and nearly the same as that seen with a new piece of polyimide tape, but there was no fluctuation in the resistance value. It should be noted that the adhesive on the metal tape was verified to be a poor electrical conductor, so the stability of the reading was due to the good contact of the bead to the surface and not due to conduction through the metal tape.

An additional experiment was run for further verification. Two thermocouples were attached to a hot plate side by side. One was attached using polyimide tape and the other a metal tape. The hot plate was turned on and the two thermocouples were monitored. The thermocouple attached with metal tape reached 147®C and stabilized. The thermocouple attached with the polyimide tape reached 127®C and stabilized. The thermocouple locations were swapped and the same result was observed. It was also noted that the thermocouple attached with metal tape rose at a faster rate and stabilized sooner. The thermocouple attached with polyimide tape was pressed down against the plate at the tip and the reading began to rise as expected due to the fact that the thermocouple bead was not in contact with the hot plate surface.

<u>Example:</u> The profile issue discussed in the, "Introduction" is an example of a trigger thermocouple that was poorly adhered to the PCB assembly surface. A reused piece of polyimide tape was used.

Solutions: Two ways to minimize or avoid the issues associated with trigger thermocouple attach are as follows:

1. Clean surface and use only new polyimide tape – It has been shown that cleaning the area with isopropyl alcohol or similar cleaner improves the adhesion of the tape. After cleaning, only a new piece of polyimide tape should be used. As discussed earlier, polyimide tape has excellent adhesion in general to the PCB surface, but it does not adhere well in the immediate area around the thermocouple bead. Through multiple profile runs, it has been shown that with cleaning and use of new tape, this tenting is generally not detrimental to achieving consistent profiles. Monitoring the peak trigger thermocouple temperature and comparing it against that established with the initial profile is therefore critical. A change in the peak temperature is a flag that may indicate there was an adhesion / thermocouple bead contact issue.
2. Clean surface and use a metal tape – Metal tapes provide the benefit of conforming well around the thermocouple bead, assuring that it is held firmly against the surface. A popsicle stick works well to form the metal tape around the bead. The PCB surface should be cleaned as discussed in item one. Any metal tape should be checked for ESD concerns.

PCB Assembly Support Method / Locations in Rework Tool

Overview: Some hot gas tools use thick rails underneath the PCB assemblies for support and some use pins. In order to achieve a repeatable profile / rework process, it is important to use the PCB assembly support systems appropriately. For example, if the PCB support rail or pin is setup directly under the trigger TC location, then the length of the board preheat event may exceed the length that was established during initial profiling. This can result in over heating the PCB and the temperature sensitive components on the assembly and may also effect the peak solder joint temperature and TAL (Time Above Liquidous). The support acts as a heatsink.

Example: In Figure 16, two different profiles were performed. Run 1 was performed with the adjustable tool support towards the bottom of the card. For Run 2, the adjustable tool support was placed directly under the trigger thermocouple position. The peak trigger thermocouple temperature observed for Run 1 was 125®C. When the same profile was repeated with the support rail directly under the trigger TC location (Run 2), the peak trigger TC temperature fell 7®C from that observed for Run 1. The board preheat time also increased by 30 seconds from Run 1 to Run 2. Though the joint temperatures remained within specs and acceptable in this case, this data highlights the sensitive nature of tool support location. It is therefore recommended to avoid placing the tool supports directly under the trigger thermocouple location for the following two reasons.

1. If the peak joint temperature readings of the approved profile are close to or just above the lower or higher limit of the specs, then running the profile with the support rail setup directly under the trigger TC location can throw the profile off the specs.
2. As shown in our example, the location of the tool support can impact the peak temperature achieved by the trigger thermocouple. If this is being used as a process monitor as recommended, then this will raise a flag and require Engineering intervention and analysis.

PCB Setup on rework tool

Profile data with & without support rail under trigger TC location

RUN 1: Support rail setup away from trigger TC

RUN 2: Support rail setup diridly under trigger TC

	RUN 1			RUN 2			Delta		
Description	Temp	TAL	Time	Temp	TAL	Time	Temp	TAL	Time
Corner Joint	215	84		211	76		4	8	
Center Joint	218	82		216	77		2	5	
Adjacent Joint	177	0		173	0		4	0	
Peak Trigger TC	125	0		118	0		7	0	
Trigger Length			390			420			30

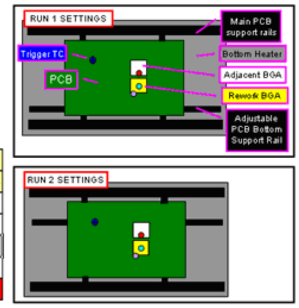

Figure 16. Impact of Adjustable Tool Support

Solution: Ideally, the CM's rework instructions should provide guidance on where to position the tool supports. At the very least though, there should be a requirement not to position the tool support directly under the trigger thermocouple position. Operators should be trained to follow this procedure and be taught why this is critical to assure a consistent and repeatable profile.

PCB Assembly Orientation in Rework Tool

Overview: PCB assembly orientation and position on the rework tool is equally important to achieve consistent hot gas rework. For actual product rework, operators must orient the PCB assembly exactly as it was when the thermal profile program was established. Not doing so can seriously impact the quality of the rework. Joint temperatures and time above liquidous can drastically change and fall outside of specification limits. Hence operators must pay attention to proper orientation during board setup on the hot gas rework tool.

Example: The data Figure 17 illustrates how part orientation can affect solder joint temperatures and the time above liquidous. Run 1 is the profile initially established for this assembly and device and Run 2 is the same profile performed with the card rotated 90®. The Run 2 data shows a significant temperature drop in thermocouples five and six which are the component solder joint temperatures. The TAL was also impacted. Run 3 shows similar readings to Run 1. Run 3 was done with the same card orientation and process setup as Run 1. The data comparison between runs is shown in the green columns.

Hot Gas Rework Profile Data Variance Due To Board Orientation Setup On Rework Tool

Board Orientation:

Eutectic Profile Data	Original Data, June 30 2008		New Data, Aug 18 2008, 11:02 PM		New Data, Aug 21 2008, 10:22 PM With Original Orientation		Delta between RUN 1 & RUN 2		Delta between RUN 1 & RUN 3	
	Joint Temp	TAL	Joint Temp	TAL	Joint Temp	TAL				
TC Description	Run 1	Run 1	Run 2	Run 2	Run 3	TAL 3	Temp	TAL	Temp	TAL
TC # 2 Corner joint	213	116	209	118	208	116	4	0	5	0
TC # 3 Corner joint	208	116	205	101	207	107	3	15	1	9
TC # 4 Center joint	213	128	212	121	213	130	0	2	0	2
TC # 5 Corner joint	210	115	202	91	207	109	8	26	3	6
TC # 6 Corner joint	219	129	208	107	214	125	11	22	5	4
TC # 7, U_ENT adjacent joint	160	0	162	0	164	0	4	0	4	0
TC # 8, U_2R3 adjacent joint	176	0	173	0	178	0	2	0	2	0
TC # 1 Trigger TC	132	0	131	0	132	0	0	0	0	0

Figure 17. Impact of Card Assembly Orientation

<u>Solution:</u> The process instructions should clearly identify the card orientation in the rework tool for each card assembly and component being reworked. An example process instruction schematic is shown in Figure 18. Operator training should also emphasize the critical nature of card orientation.

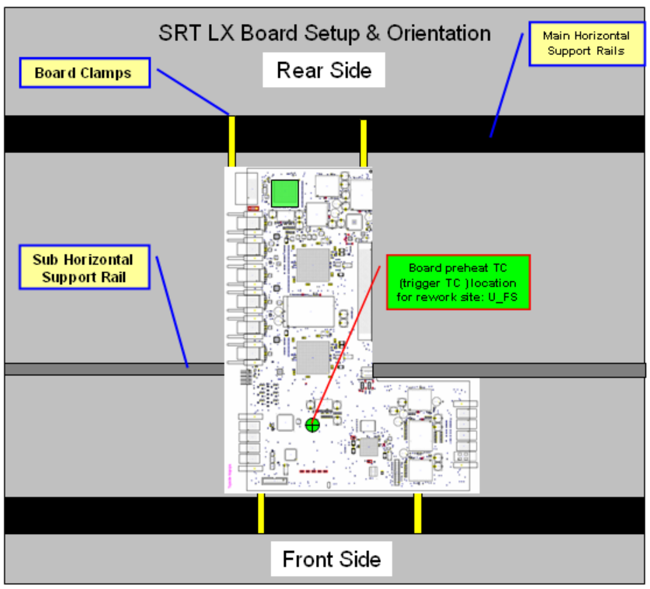

Figure 18. Example Schematic in Rework Process Documentation

Initial Profiling Methodology

<u>Overview:</u> The hot gas rework thermal profiling methodology is important in achieving a consistent profile of a given device. Selecting an appropriate set of profile cards is important. Card assemblies may be routed to rework from different points in the assembly process. Three possible scenarios are provided here for illustration purposes.

1. After initial SMT (surface mount technology) reflow, defective components may be identified by visual inspection or x-ray.
2. Assemblies may also be routed to rework post ICT (In Circuit Test) or functional test, and prior to heatsink attach.
3. Parts may also be routed to rework post heatsink attach.

The thermal mass of the card assembly is likely to be very different for each of the three scenarios listed and therefore requires multiple rework thermal profile cards. This is because the thermal profile program is likely to be different for each card assembly configuration.

It is also important to determine how many thermocouples are required to adequately characterize and analyze the thermal profile. Many times due to the complexity and component density, multiple profile cards of the same type (i.e. – bill of material) are required as not all thermocouples can be placed in one card. This is due to the fact that the high number of thermocouples makes the card cumbersome to work with as well as potentially adding excessive thermal mass. When multiple components on one card assembly need to be thermal profiled for rework, this scenario is likely to occur.

Solder joint thermocouples are typically attached in one of two ways

1. Drill from bottom side up to the solder joint. Insert the thermocouple and apply an adhesive (epoxy or ultraviolet glue for example). Cure the glue. This method has some risks which can affect temperature accuracy.
    a. The thermocouple bead may be exposed to direct heat during profiling if it is not centered well within the device solder joint.
    b. The bead may slip down into the PCB and be positioned below the solder joint level during profiling.
2. Remove the component. Redress the site. Attach the thermocouple to the pin (pad). Screen the solder paste. Place the component and reflow the device.

When choosing locations to place solder joint thermocouples, it is important to study the pin functions. Signal pins and ground pins will likely heat at very different rates due to the thermal paths. Therefore both types of pins should be thermocoupled to assure that both are meeting the desired result.

The position and support of the card assembly in the hot gas rework tool is also critical. Often times a secondary support fixture is necessary. Several card assembly positions may need to be evaluated in trying to establish an optimized profile. The trigger thermocouple location is defined in conjunction with defining the card orientation and support method. It is has been found that strain gauges should be used to confirm the card support methodology is adequate.

The card assembly starting temperature prior to rework is also a factor that is often overlooked. When multiple components need to be reworked on the same card, a common practice is to immediately move from the completion of rework of the first component to starting rework on the second. This generally results in the starting card assembly temperature being much higher than that established during the profiling phase. Experience has shown that this can have an affect on the resultant profile. It is recommended that the starting card assembly temperature be very near ambient prior to starting any subsequent rework operation. If your manufacturing scenario requires reworking card assemblies while the card is still hot, the impact of this requirement should be evaluated as part of the profile establishing phase. It should be noted, card assemblies, and especially the solder joints, can be more susceptible to handling induced damage while at elevated temperature.

Lastly, the physical location of the rework tool can play a role in profile consistency. Experience has shown that irregular ambient airflow in the vicinity of the tool can have a major impact on a rework profile. The hot gas rework tool should not be placed directly under heating/air conditioning ducts or near fans/blowers. The tool should also be placed away from entry doors as this can also create an unstable ambient environment.

Record all events, steps, tools, heat shields, trigger thermocouple location, and processes during initial profiling. Define the complete process in the documentation used to control the operation.

STEPS IN ESTABLISHING A CONSISTENT PROFILE

Follow this sequence of steps to assure a consistent and repeatable profile.

1. Locate the rework tool in an area which has a stable ambient environment.
2. Establish the card assembly support methodology and orientation.
3. Select a trigger thermocouple location and apply the thermocouple securely to the PCB surface using one of the methods discussed in this paper.
4. Run a profile card, with thermocouples inserted into the solder joints, and adjust the tool parameters until the desired result is achieved. During this step, the trigger thermocouple should not be moved. As discussed earlier, it is critical that for each profile run, the board be allowed to cool to ambient before attempting another trial.
5. Note the peak temperature reached by the trigger thermocouple after establishing an acceptable profile.
6. Move the trigger thermocouple roughly 1 cm from its original location and repeat. This is done to understand the sensitivity of the trigger thermocouple location for this particular rework location. If the profile is no longer acceptable or if the trigger thermocouple peak temperature is significantly different, then placement location is a critical parameter. In this case, a template may be the best method.
7. Establish the trigger thermocouple location method to be used (i.e. – schematic in process instructions, template, etc). This will be influenced by the level of sensitivity of the part.
8. Run multiple profiles, with removal and replacement of the trigger thermocouple.
9. Establish a target trigger thermocouple peak temperature and tolerance. This target temperature and tolerance are recorded in the process instructions and are used as a control. Operators are to note the peak temperature at the completion of each rework and compare to the acceptable range. If the value falls outside of this range, Engineering is contacted for assistance and product disposition. Experience has shown that a tolerance of +/-5®C for the peak trigger thermocouple temperature is achievable and assures a repeatable profile.

CONCLUSIONS

Hot gas rework will continue to be a critical process for electronic assembly. Due to the critical nature of the operation, rework must be more than a “press go” and walk away until finished process. Proper setup, control, and monitoring will assure that a high quality and reliable product results. This is especially important to assure that the proper metallurgical structure is formed. Rework CMs need to have a focus on defining clear and precise process instructions, especially as it relates to positioning of the tool control (trigger) thermocouple. These instructions need to be clear enough to assure the thermocouple is positioned in the same location each and every time rework is performed. There also needs to be a focus on establishing a reliable trigger thermocouple attach method, such that consistent and repeatable contact is maintained with the PCB. Reuse of thermocouple attach tape is not a good practice. Rework CMs should also take advantage of the trigger thermocouple temperature data output available from most hot gas rework tools. This data can be used as an indicator or process monitor to verify a successful rework has been completed. This is done by taking some extra time during the initial rework profiling stage. Multiple profiling runs should be performed, to establish an expected peak trigger thermocouple temperature and tolerance. When the peak temperature falls within this window, this provides another indicator that the rework operation was successful. Often visual inspection and electrical test are the only methods used to verify a successful rework. Visual inspection is difficult, usually requiring a mirror, and can only evaluate the very outer rows of the array device. Electrical test confirms metallurgical connection, but does not provide assess metallurgical structure. Following these recommended procedures and controls will assure the best opportunity for rework success.

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DEFINITION OF TERMS

- BGA – Ball Grid Array
- CM – Contract Manufacturer
- ICT – In Circuit Test
- PCB – Printed Circuit Board
- PTH – Plated Through Hole
- SMT – Surface Mount Technology
- TAL – Time Above Liquidous
- TC - Thermocouple