INEMI Rework Machine Temperature Tolerance and Repeatability Study

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Abstract
Currently little data exists on temperature repeatability of BGA/CSP rework machine equipment. This is an issue especially for lead-free rework as the temperatures during lead-free BGA/CSP rework are likely to be higher than reflow soldering, leading to potential component and board temperature related issues. A series of evaluations was conducted on rework equipment from four rework machine equipment suppliers. The BGA/CSP rework machine repeatability and tolerance temperature study used a fixed thermal profile with temperature measurement output on equipment specifically designed for BGA/CSP rework machines. The temperature input was a lead-free rework profile developed by each supplier on a PBGA544 component on a 135mil (3.4mm) thick test vehicle board. This lead-free rework profile was run on the rework machine 10 times. Temperature peaks and durations were recorded at the 6 different temperature locations on the temperature measurement equipment placed within the rework machine.

In Phase 1 of the program each rework machine supplier recorded temperatures using its defined lead-free profile with a specific rework machine. In Phase 2, each supplier repeated these tests on a different machine of the same model. A comparison was then done to analyze the temperature and time data from Phases 1 and 2 to determine rework machine temperature repeatability and tolerances.

Introduction
With the move to lead-free soldering, required processing temperatures have increased for both components and boards used for assembly and rework. Lead-free process temperatures for BGA/CSP rework are typically higher than lead-free reflow soldering. As a result, component/board peak temperatures are close to or exceed the maximum temperatures rating for lead-free components indicated in the J-STD-020D standard (Ref. 1).

Understanding the temperature repeatability of rework equipment is important so that manufacturing guidelines can be established to prevent component temperatures from exceeding temperature and time limits. Feedback provided to rework machine suppliers is important so that improvements can be made during development of new equipment and to better monitor existing equipment during manufacturing rework operations. The key objective of this program was to identify rework temperature tolerances and times as recorded and reported by several rework machine suppliers. These results are discussed in the following sections.

Experimental
The initial part of the evaluation was to develop a lead-free rework profile on a PBGA544 component on the INEMI Payette test vehicle board using the specific rework equipment. Once the lead-free rework profile was developed, the temperature set points and times used were fixed to use in Phases 1 and 2. Phase 1 involved using these set points for a specific machine and equipment model with the rework machine temperature monitoring equipment. Phase 2 involved using the same set points with the rework machine temperature monitoring equipment but changing the actual rework machine used but not its model number. The details of this work are shown in the following sections.

BGA Rework Temperature Profiling on INEMI Payette Test Vehicle Board
Initially, each rework machine supplier had to develop a lead-free rework profile for a PBGA544 component (35mmx 35mm, 1mm pitch) used on the 135mil (3.4mm) thick INEMI Payette board with board dimensions 7 x 17 inch as shown in Figure 1. Once this profile had been developed, this rework profile would be used on the rework machine temperature measurement equipment specifically designed for assessing temperature profiles on rework equipment.

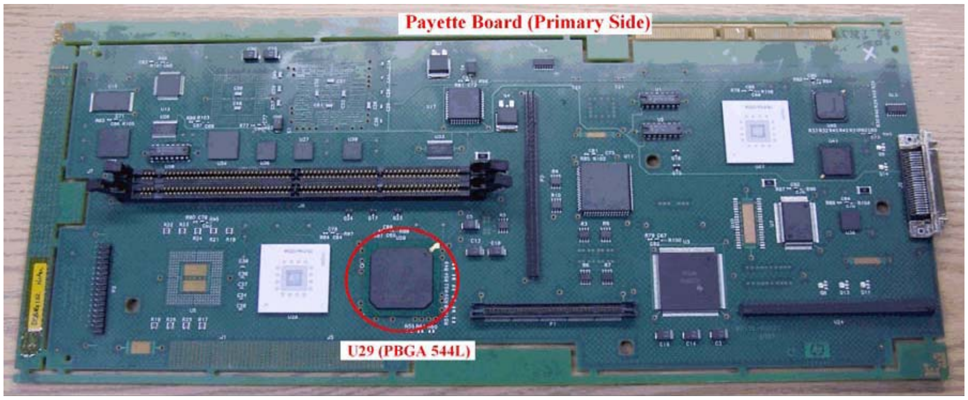


Figure 1: INEMI Payette test vehicle board

Thermocouples were installed on the PBGA on specific locations in the solder joints and on the top of the component to measure the temperature during rework. This was done by removing the component and drilling holes into the board at specific locations so that the thermocouples could be placed through the board and contact specific target board pads. Thermocouple tips were glued by thermally conductive adhesive to ensure a good thermal connection with the target solder joint. Then a new component was installed. After installation, another thermocouple was installed onto the topside surface of the component. Examples of thermocouples applied to the PBGA are shown in Figures 2 and 3 with an overall view of thermocouple locations shown in Figure 4.

Figure 2: Topside thermocouple locations

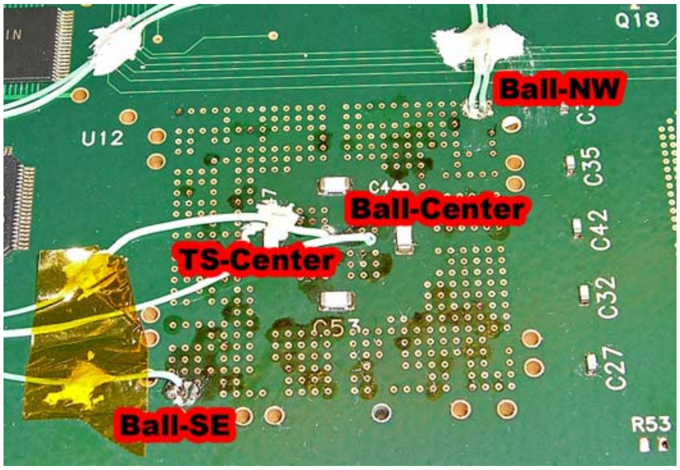


Figure 3: Thermocouple placement through the bottom-side of the board

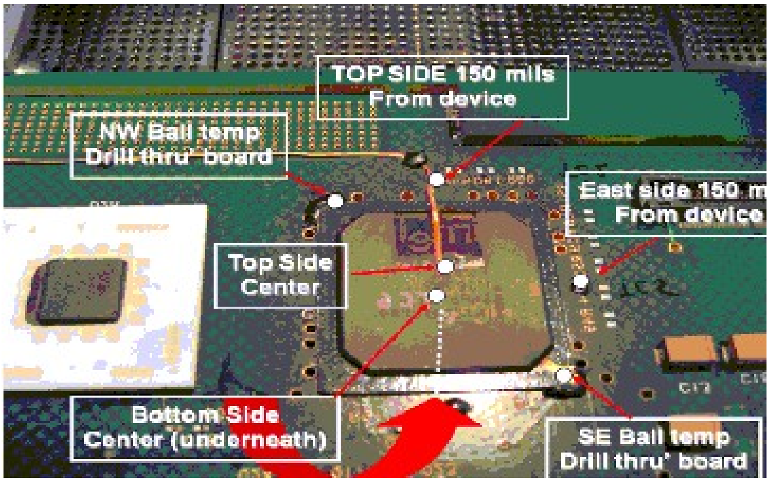
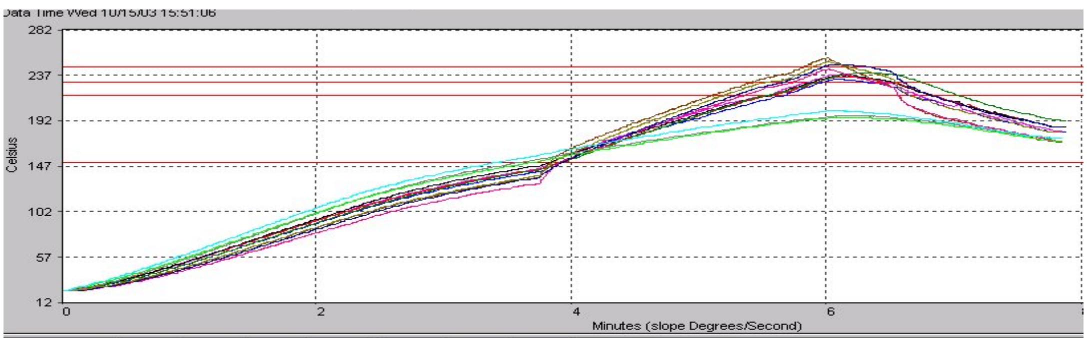


Figure 4: Overall view of thermocouple locations

The following guidelines were supplied to each supplier for use in developing their lead-free rework profile:

- Minimum for Temperature measurements at solder joint locations at the North West Corner Solder Joint, South East Corner, and Center Solder Joint to be in the range 230°C to 235°C.
- Time above liquidus (217°C) to be in the range of 50 to 90 sec.
- Solder Joint and Component Top Temperatures to be in the range from 230°C to 250°C.

The INEMI Payette board rework profile data was submitted to the INEMI group for approval before proceeding to the next stage. Once approved, this profile became the default lead-free rework profile to be used in subsequent stages. If used, hot air/gas rework nozzles were to be positioned approximately 0.030" (0.75mm) above the PCB surface during rework. Shown in Figure 5 is a typical profile developed for the PBGA544 location on the INEMI Payette board.



	Peak	Max Rising Slope	Max Falling Slope	Rising Time Between 150/217	Total Time Above 217	Total Time Above 230	Total Time Above 245
1 Bot Left (1)	236.8	1.02	-0.98	103.04	69.44	35.07	0.00
2 Top Left	232.2	0.99	-0.97	107.46	58.02	19.58	0.00
3 Top Right	235.2	0.83	-0.74	101.64	74.19	34.76	0.00
4 Bot Right	236.1	0.86	-0.77	103.85	75.05	36.59	0.00
5 Center	239.3	0.80	-0.76	96.71	89.47	48.66	0.00
6 West .150"	253.7	2.12	-1.84	77.36	86.69	59.86	18.49
7 North .150"	242.7	1.87	-1.76	86.88	72.28	37.72	0.00
8 Top of Pkg	247.5	1.33	-1.45	81.52	92.27	55.52	19.81
9 Edge of Pkg	250.0	1.61	-1.59	80.57	87.35	59.87	16.88
10 Bot Pkg SJ	196.8	0.79	-0.40	155.90	0.00	0.00	0.00
11 Bot Pkg SJ	195.2	0.80	-0.36	149.24	0.00	0.00	0.00
12 Bot Pkg Edge	201.8	0.79	-0.38	159.02	0.00	0.00	0.00

Figure 5: Typical Lead-free Rework Profile developed on the INEMI Payette board for the PBGA544 at U29 location

The temperatures of locations at the PBGA on the INEMI Payette Board were monitored with focus on Peak Temperature and Time Above Liquidus (TAL).

Phase 1

After developing the INEMI Payette board lead-free rework profile, each supplier ran the same lead-free rework profile on its Phase 1 rework machine ten times. Phase 1 used the rework machine temperature measurement equipment on which six thermocouples were embedded. Measurement of temperature peaks were recorded at the six different temperature locations on the measurement equipment placed within the rework machine. A typical set up of the rework machine temperature measurement equipment is shown in Figure 6.

Figure 6: Typical setup of rework machine temperature measurement equipment placed in the rework machine

The rework machine temperature measurement equipment thermocouple locations are shown in Figure 7 and described below:

1. Two thermocouples at corners of an imaginary 35mm package on the topside (Locations on North-West [TC2] and South-East [TC5] corners)

2. One thermocouple location on the bottom side of the board on the corner of an imaginary 35mm package (North-East corner [TC4])

3. Two thermocouples at the center of an imaginary package
(1 topside center [TC1] and 1 bottom side center [TC6])

4. One topside thermocouple located 150 mils (3.8mm) away from the component in the North direction [TC3]

A total of 6 Thermocouple locations were used [TC1-TC6] and recorded on the rework machine temperature measuring equipment.

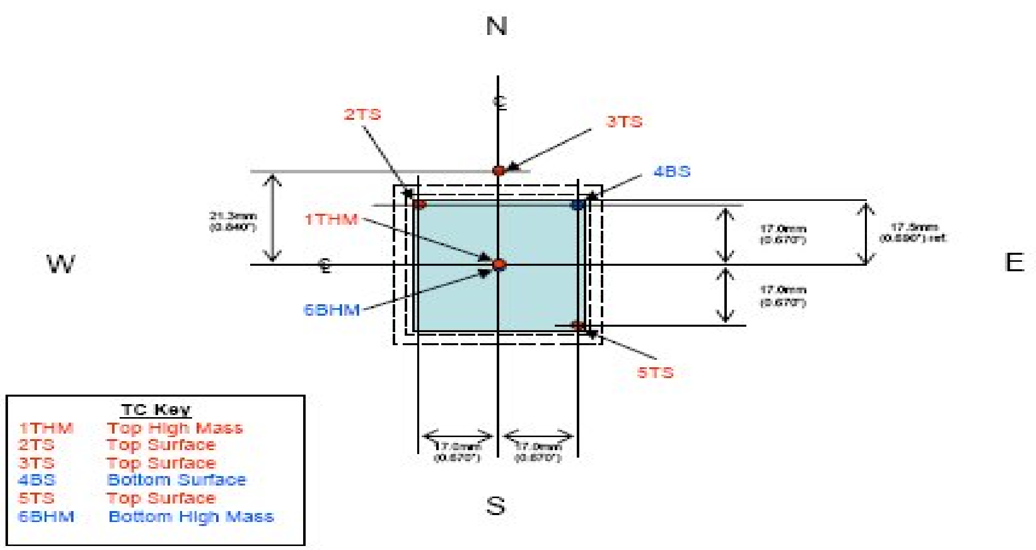


Figure 7: Rework Machine Temperature Measurement Equipment Thermocouple Locations

The rework machine temperature measurement equipment was cooled down to room temperature after each lead-free rework run to ensure a consistent temperature prior to each run. After each run, the measurement equipment was removed from the rework machine and fan-cooled to room temperature for 10 minutes. The rework measurement equipment temperature was monitored for another 5 minutes to insure that its temperature did not exceed 30°C.

During each of the ten runs, the rework machine measurement equipment recorded Peak Temperature, Time above 217°C, Time between 150°C and 217°C and Time within 5°C of the Peak Temperature. As specified for the INEMI Payette board, hot air/ gas rework systems using a rework nozzle were adjusted to a 30mil (0.75mm) gap above the board surface. The flatness of the nozzle/head was also checked. In addition the same airflow rates used in the initial part of the work for hot air gas rework machines were used for Phases 1 and 2. On completion of Phase 1 after group approval of the data, each rework machine supplier moved on to Phase 2.

Phase 2

The same test as Phase 1 was done in Phase 2 at the rework manufacturer with the rework machine temperature measurement equipment with the same rework machine model but with a different rework machine. The data from each of the two stages was compared to determine and improve rework machine temperature repeatability and tolerances, which is discussed in the next section.

Results and Discussion

Phase 1

Average rework machine peak temperatures over the ten runs across the six thermocouples for the 4 machine suppliers in Phase 1 are shown in Tables 1, 2,3 and 4. In addition the standard deviation, minimum, maximum and repeatability values were recorded. The evaluation objective was not to evaluate the actual peak temperatures but to assess the variation in peak temperature occurring over the 10 rework runs. TC3 on Machine B and TC4 on Machine D in Phase 1 had temperature measurement reading issues so were not used in calculation of the averages.

Table 1: Phase 1 Peak Temperature Results for Rework Machine A

Machine A (Phase 1)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	274	1.5	271	276	7.7
TC2 Top North West corner	309	2.5	304	313	12.9
TC3 Top board North 150 mils	264	2.1	260	267	10.8
TC4 Bottom North East Corner	318	1.8	315	320	9.3
TC5 Top South East Corner	279	1.8	275	281	9.3
TC6 Bottom center	272	2.1	267	274	10.8
				Average	10.1

Table 2: Phase 1 Peak Temperature Results for Rework Machine B

Machine B (Phase 1)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	284.4	0.8	283	285	4.3
TC2 Top North West corner	276.3	1.5	275	280	7.7
TC3 Top board North 150 mils					
TC4 Bottom North East Corner	234.3	0.7	233	235	3.5
TC5 Top South East Corner	291.1	1.7	288	293	8.9
TC6 Bottom center	238.8	1.1	237	240	5.8
				Average	6.1

Table 3: Phase 1 Peak Temperature Results for Rework Machine C

Machine C (Phase 1)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	216.8	3.1	213	222.5	16.0
TC2 Top North West corner	239	1.9	237	241.9	9.8
TC3 Top board North 150 mils	237.6	2.3	235	241.3	11.8
TC4 Bottom North East Corner	265	3	259	268.6	15.5
TC5 Top South East Corner	243.1	2.6	238	246	13.4
TC6 Bottom center	269.2	3.9	263	273.4	20.1
				Average	14.4

Table 4: Phase 1 Peak Temperature Results for Rework Machine D

Machine D (Phase 1)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	292.6	0.5	292	293	2.7
TC2 Top North West corner	269.4	0.8	268	271	4.3
TC3 Top board North 150 mils	278	0.5	277	279	2.4
TC4 Bottom North East Corner					
TC5 Top South East Corner	289	0.0	289	289	0.0
TC6 Bottom center	243.9	0.3	243	244	1.6
				Average	2.2

The machine (or gage) repeatability with 99% confidence level was calculated in the Tables by multiplying 5.15 by the Standard Deviation with a graphical illustration of machine repeatability shown in Figure 8.

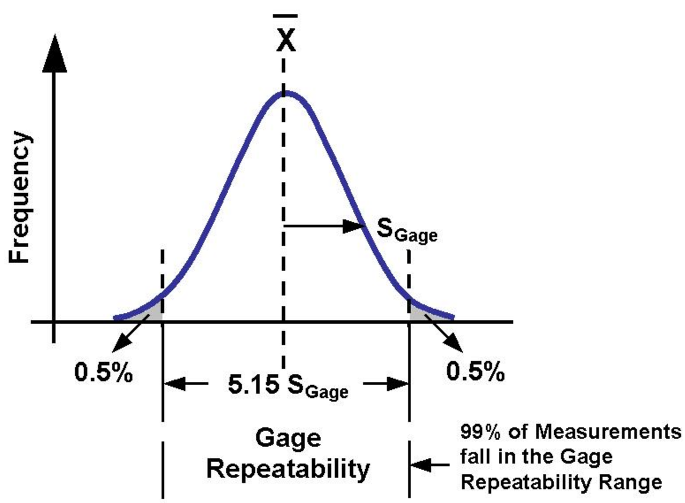


Figure 8: Graphical representation showing how 99% of the measurements fall in the gage repeatability range

From Table 1, the temperature repeatability for Machine A was 10°C with 99% confidence level. As indicated in Figure 8, this meant that 99% of the time the peak temperature would vary by +/- 5°C around the average peak temperature. If the component top surface peak temperature was recorded as 255°C, it could actually vary by as much as 5°C either side of 255°C (as low as 250°C and as high as 260°C). The temperature repeatability of Machine B from Table 2 was 6°C with 99% confidence level with +/-3°C around the peak. The temperature repeatability of Machine C from Table 3 was 14°C with 99% confidence level with +/-7°C around the peak. The temperature repeatability of Machine D from Table 4 was 2°C with 99% confidence level with +/-1°C around the peak.

The results for Machine C were higher than expected because there was a specific feature of that machine which caused it to use closed loop temperature control of the machine so that specific set points developed during the BGA component rework profiling could not be replicated which accounted for the larger temperature variation during the rework runs in Phase 1.

Phase 2

The rework machine temperature measurement equipment results for the peak temperature for the four machine suppliers are shown in Tables 5, 6,7 and 8. TC3 and TC4 on Machine B and TC4 on Machine D in Phase 2 had temperature measurement reading issues so were not used in calculation of the averages.

Table 5: Phase 2 Peak Temperature Results for Rework Machine A

Machine A (Phase 2)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	288	1.2	286	290	6.2
TC2 Top North West corner	283	2.9	277	287	14.9
TC3 Top board North 150 mils	267	3.9	261	273	20.1
TC4 Bottom North East Corner	319	2.2	314	321	11.3
TC5 Top South East Corner	283	1.8	280	286	9.3
TC6 Bottom center	314	1.8	312	318	9.3
				Average	11.8

Table 6: Phase 2 Peak Temperature Results for Rework Machine B

Machine B (Phase 2)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	288.7	1.1	286	290	5.5
TC2 Top North West corner	278.4	1.1	276	279	5.5
TC3 Top board North 150 mils					
TC4 Bottom North East Corner					
TC5 Top South East Corner	298.7	1.8	295	301	9.1
TC6 Bottom center	235.1	2.2	232	238	11.2
				Average	7.8

Table 7: Phase 2 Peak Temperature Results for Rework Machine C

Machine C (Phase 2)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	211.0	2.2	208	215.7	11.5
TC2 Top North West corner	239.4	1.8	237	243.4	9.0
TC3 Top board North 150 mils	237.1	1.8	235	240.7	9.3
TC4 Bottom North East Corner	275.5	3.2	269	278.6	16.6
TC5 Top South East Corner	243.0	1.3	241	244.9	6.6
TC6 Bottom center	284.7	3.5	278	288.2	18.1
				Average	11.8

Table 8: Phase 2 Peak Temperature Results for Rework Machine D

Machine D (Phase 2)					
Rework Peak Temperature	Average	StDev	Min	Max	Repeatability (99% confidence)
TC1 Top Center	290.8	0.6	290	292	3.2
TC2 Top North West corner	264.2	0.9	263	266	4.7
TC3 Top board North 150 mils	274.0	0.9	273	276	4.8
TC4 Bottom North East Corner					
TC5 Top South East Corner	287.0	0.7	286	288	3.5
TC6 Bottom center	240.9	0.7	240	242	3.8
				Average	4.0

From Table 5, the temperature repeatability of Machine A was 12°C with 99% confidence level. This meant that 99% of the time the peak temperature would vary by +/- 6°C around the average peak temperature. So if the component top surface peak temperature was recorded as 254°C, it could actually vary by as much as 6°C either side of 254°C (as low as 248°C and as high as 260°C). The temperature repeatability of Machine B from Table 6 was 8°C with 99% confidence level with +/- 4°C around the peak. The temperature repeatability of Machine C from Table 7 was 12°C with 99% confidence level with +/-6°C around the peak. The temperature repeatability of Machine D from Table 8 was 4°C with 99% confidence level with +/-2°C around the peak.

Again the results for Machine C were higher than expected because there was a specific feature of that machine which caused it to use closed loop temperature control of the machine so that the specific set points developed for the BGA component rework profiling could not be replicated which accounted for the larger temperature variation during the rework runs in Phase 2 similar to Phase 1.

Comparison of Phase 1 and Phase 2 Results

Based on comparing the results of Phases 1 and 2 in Table 9, the average machine repeatability across different rework machine suppliers for Phases 1 and 2 are both around +/-4°C. If we add in the thermocouple measurement repeatability of +/-1°C, the total machine repeatability is +/-5°C. So if the component top surface peak temperature was recorded as 255°C, it could actually vary by as much as 5°C either side of 255°C (as low as 250°C and as high as 260°C).

Table 9: Combined Phase 1 and 2 Machine Repeatability Temperature Results

Machine Repeatability	Typical	Worst Case
Machine A, Phase 1	+/- 5ºC	TBD
Machine B, Phase 1	+/- 3ºC	TBD
Machine C, Phase 1	+/- 7ºC	TBD
Machine D, Phase 1	+/- 1ºC	TBD
Machine A, Phase 2	+/- 6ºC	TBD
Machine B, Phase 2	+/- 4ºC	TBD
Machine C, Phase 2	+/- 6ºC	TBD
Machine D, Phase 2	+/- 2ºC	TBD
Thermocouple Repeatability	+/- 1ºC	+/- 2ºC

Based on the results, we can see that there are variations in temperature repeatability across rework machines of the same model. It underlines the importance of conducting these types of tests because higher temperatures are usually encountered during lead-free area array rework. We can see an average repeatability across the four machines in the two phases to be +/-5ºC. As a guideline, previous work on a reflow oven showed a temperature repeatability of around +/- 2ºC (Ref. 2) but the methodology used to produce the data on the reflow oven testing was different so a like to like comparison could not be made.

Conclusions

The repeatability tests for rework machines from four rework machine suppliers indicated an average repeatability of +/- 5ºC. The data would be useful for each rework equipment supplier to understand temperature repeatability of their specific equipment and determine what steps would be needed to improve it. The rework machine temperature profiler was found to be fairly effective in measuring temperature repeatability of the rework machine equipment.

The work highlighted the need to keep tighter tolerances in the form of periodic machine calibrations and temperature profiling to prevent component temperature issues during lead-free rework.

Future Work

The next stage of the evaluation, Phase 3, would assess the rework temperature repeatability of the same model of machine from each of the four rework machine suppliers at an OEM/EMS manufacturing site. The key objective would be to identify variations in temperature repeatability between rework machines built on the rework machine supplier factory floor and those installed in the field on the manufacturing floor. Assessments would also include variations in airflow used for the rework machine and its effect on temperature repeatability. Other areas which may influence temperature repeatability would be pre-heater settings, power supply settings, nozzle design and nozzle height which may be considered in future testing.

The data from this work would be supplied to standard groups such as IPC/JEDEC J-STD-020. Rework temperature tolerance data could be used in helping to more accurately specify component temperature ratings and to provide rework equipment suppliers and users rework temperature guard bands. Either the component temperature ratings would go up or rework machine suppliers could improve the temperature repeatability of their equipment. For example if the maximum temperature rating was 260ºC, the maximum target component top temperature would be between 250ºC to 255ºC to account for machine temperature variation of +/-5ºC. While the discussion has focused on higher peak temperatures being encountered for the component, we also need to be aware of the temperature variation at the lower solder joint temperatures. If the solder joint temperature was targeted at 230ºC minimum, it may need to be raised to 235ºC to account for the machine temperature variation of +/- 5ºC so that reworked solder joint temperatures may not go too low to cause cold or open solder joints.

Acknowledgements

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References

(1) IPC/ JEDEC J-STD-020D Standard, Moisture/ Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices, June 2007.

(2) Lead-Free Electronics: iNEMI Projects Lead to Successful Manufacturing, Table 8.5, p347, November 2007, IEEE Wiley.