REFLOW PROFILING FOR NEXT-GENERATION SOLDER ALLOYS

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ABSTRACT:

After the Pb-free transition, most of the industry settled on using predominantly SAC305 solders. More than a decade later, a large segment of the industry is moving to adopt modified SAC alloys, as well as new Pb-free alloys for higher reliability, or even low melting point alloys. These choices really expand the playbook of possible reflow profiles.

This paper will review common profile shapes and recipes, showing data for how they differ in the resulting solder joints. There will also be a discussion on the critical points of successful reflow profiling for the wider range of Pb-free alloys now on the market.

In addition, as high-temperature applications that traditionally used high-Pb alloys for high operating temperatures come close to losing RoHS exemptions, new alloys are emerging to achieve the high performance expectations associated with applications in this range.

KEY WORDS: high-reliability, SAC alloys, reflow profiling, reflow process window

INTRODUCTION:

Process development and continuous improvement are critical to success in PCB assembly. The reflow process is at the top of the list for optimization. Companies with a high mix of assembly designs and materials are even more challenged with using the best reflow process for each one. New materials and process constraints have also limited process windows, making assemblies that much more sensitive to profile. To keep up with these industry needs, reflow profiling software and best practices have continued to develop. This experiment focused on developing the best profile for next generation SAC alloys and how to best modify the reflow process when a new material is chosen.

Next Generation SAC Alloys:

The introduction of RoHS regulations in the electronics industry has prompted extensive research into the development of Pb-free soldering alloys with the reliability the industry came to expect from SnPb alloys. SAC305 (96.5% Sn, 3.0% Ag, and 0.5% Cu) has emerged as the go-to lead-free alloy by popular choice. SAC305 has proven itself a worthy replacement for Sn63, although requirements in the automotive, aerospace, and military industries have driven further research for alloys with even higher reliability expectations.

Elemental additions of indium, bismuth, antimony, and nickel have been candidates for the next generation Pb-free alloys. Different compositions of these elements added into a tin-silver-copper matrix can improve thermal fatigue and strength. However, developing the ideal combination to meet all of the desired properties has proven to have limitations within the Pb-free space. The next generation lead-free alloys have been developed as solutions to finding the perfect balance between being strong and flexible. When added, antimony (Sb) increases tensile strength, while bismuth (Bi) can make the alloy more brittle. A balance of ductility and rigidity in a solder alloy needs to be achieved in order to have a reliable solder joint for high reliability under a wide service temperature environment[1].

It is important to consider the plastic or pasty range of these alloys and how it affects the wetting characteristics of the solder. The plastic range exists for any non-eutectic alloy and is the temperature range between the solidus and the liquidus of the alloy where the alloy is neither fully solid nor fully liquid but instead has a pasty-type consistency. If an alloy has a wide plastic range (large difference between the liquidus and solidus temperatures), the wetting rate and also the solidification rate will be slow. If an alloy is eutectic (where the liquidus and solidus temperatures are equal) the wetting and solidification rates will be much quicker. A eutectic solder may be ideal for reducing voiding, however, it can introduce tombstoning defects on passive components.

An experiment was conducted to investigate how a selection of Pb-free solder alloys perform under different reflow profiles. Five profiles were developed for use on six different lead-free alloys—SAC305, and five other next generation alloys. Table 1 shows the composition of the alloys as well as the liquidus and solidus temperatures of each.

Table 1: Selected solder alloy summary

Solidus (°C)	Liquidus (°C)	Alloy Ref	Flux	Composition (%/Element)									
175	187	**A**	B	77.2	Sn	10	In	2.8	Ag				
205	215	**B**	A	91.5	Sn	2.25	Ag	0.5	Cu	6	Bi		
217	220	**SAC305**	A	96.5	Sn	3	Ag	0.5	Cu				
217	227	**D**	C	99	Sn	0.3	Ag	0.7	Cu				
224	228	**E**	A	89.3	Sn	3.8	Ag	0.9	Cu	5.5	Sb	0.5	In
224	233	**F**	A	90.6	Sn	3.2	Ag	0.7	Cu	5.5	Sb		

Alloys A and B would be considered mid-range melting point alloys. Since the SnPb eutectic alloy melts at 183°C, Pb-free replacements were highly desired in the same temperature range. This design criteria was not met with SAC305, which is much closer to the maximum processing temperature for some common board materials and components. Alloys D, E, and F have melting points close to SAC305, but the wider pasty ranges bring the liquidus closer to other limiting parameters, limiting the reflow window, and increasing the importance of precise reflow profiling.

Alloy A contains 77.2% Sn, 10% In, and 2.8% Ag. It has proven itself worthy in the mobile and handheld device market for its performance with shock and vibration testing. Indium is a soft element and for that reason, this composition with 10% indium helps with shock resistance. However, the melting temperature of this alloy is quite less than the baseline SAC305. With a liquidus of 187°C, it is obvious that the reflow profile designed for an alloy that melts at 220°C is not ideal for this alloy.

Alloy B is one of three alloys developed[2] by Celestica for a reduced temperature melting point with acceptable reliability. These three alloys are lead-free alloys containing at least tin, silver, and bismuth. The aim of adding bismuth to these lead-free solders is to reduce the melting temperature of the alloy intending to reduce process temperatures. Using lower process temperatures presents the opportunity to use assembly components and boards that are generally too heat sensitive for the conventional SAC305 solder. Also, the low silver content in the alloy reduces the formation of brittle SnAg intermetallics, thus improving shock and drop performance. In addition to the other two Celestica alloys, alloy E contains a small amount of copper to lessen the opportunity for copper dissolution.

Alloy C is tin-silver-copper with less silver than SAC305. With only 0.3% silver, drop shock resistance is improved along with significant reduction in cost. Consumer electronics applications often consider this alloy for these reasons.

Alloys E and F were developed[1] for enhanced reliability over SAC305 in thermal cycling as well as better resistance to higher temperatures in harsh operating environments.

Reflow Profiling:

Reflow profiling is a technique to accurately measure the temperatures experienced by different components and areas of the assembly during the reflow process. It is critical to ensure appropriate process parameters on all assemblies. Merely assessing the oven zone settings is not sufficient to fully understand how an assembly reflows. Boards and components of different densities/weights will heat up at different rates. For example, if a new board design is adopted with more layers of copper, in a worst case scenario, the existing profile will not achieve the expected results by not resulting in high enough temperatures to achieve good soldering.

There is a difference between the oven zone settings and the profile itself. The settings are just the read out of the air temperatures of the zones. What the board and the components actually recognize is the profile. The profile is the temperature that the components recognize on the populated board. Again, it is important to use a populated board because different components absorb heat at different rates. Different profiles will result if components are not present.

First, setting up your board correctly for profiling is just as important as the profile itself. A fully populated board needs to be used to emulate a board that is used on a production line. Different components take different times to heat up and cool down, therefore giving a different profile than a bare board. Thermocouples should be soldered to the board with a high-temperature solder or attached with aluminum, heat-conductive tape before running it through the reflow oven to profile. The thermocouple tip should not be twisted and should be attached to the lead of the component where the solder connects it to the board. If using aluminum conductive tape, ensure that the end of the thermocouple is completely encapsulated by the tape. The thermocouple won't get an accurate reading if it's exposed to the air. If there is a concern that it could be exposed to the air, add Kapton tape around the edges of the aluminum tape for reinforcement. It can also be used to attach the wire a couple of inches behind the thermocouple as tension relief. Because Kapton tape is not thermally conductive, it should not be used to attach the thermocouples to the board.

The first thermocouple to be placed on the board is the air thermocouple and should be lifted slightly off the front of the leading edge of the board. This thermocouple is used to read the air temperature of the oven while the other thermocouples read the temperatures of other components. The remaining thermocouples should be used on a variety of different components because they feel the heat of the oven differently. This will give the most accurate profile for the board.

BGAs and BTCs require additional consideration because they do not possess typical leads like QFPs. Therefore the attachment of the thermocouples has to change in order for the board to be profiled correctly. For BGAs and BTCs you need to drill up through the board to where the center of a solder joint will be. The thermocouple will be fed through the board and take reading where the solder will be joining the component and board together. This will give an accurate reading of the solder during reflow.

After the thermocouples have been attached and the oven settings have been loaded and equilibrated, the board and profiler can be sent through the oven for measurement. The profiler will need to be inside a protective case to make sure the electronics survive this journey. All of the thermocouples will measure their respective thermal profile during this time. The first profile measured is typically a baseline for analysis and optimization.

There are different sections within a profile: preheat, pre-reflow, reflow, and cooling. The preheat section establishes the ramp rate of the PCB assembly[3]. Preheating helps to evolve flux solvents and limit thermal shock to the components. The ramp rate should be 0.5–2.0°C/second and depends greatly on the belt speed[4].

The pre-reflow section is where the flux is activated. Once the flux is activated, the chemical reaction removes the surface oxides from both the component leads and PCB pads to promote soldering once the solder becomes molten. This section is a common area of focus to control, most commonly being modified to include a soak.

During the reflow section or time above liquidus (TAL), the alloy creates the mechanical, electrical, and thermally conductive bond. This is done through formation of intermetallic compounds. Typically the TAL is 30–90 seconds to form sufficient intermetallic species[4]. The highest or peak temperature should be 15 to 25°C above liquidus[5]. The most important thing when considering the peak temperature is not to exceed the component temperature limits. The melting points of these alloys are closer to the limits of these components. Therefore, these profiles will have smaller windows and tighter limits.

The cooling section determines the grain structure of the solder joint. A fine grain structure is typically preferred and will form when the cooling is rapid. There would be increased stress on the solder joint if it cools too fast; about 4°C/second would be the ideal cooling rate[4].

There are two general profile shapes used for reflow profiling. There is ramp-to-peak (RTP) also known as ramp-to-spike profile. The other profile is a soak profile or a ramp/soak/spike profile (RSS). A RTP profile is a linear graph straight to the peak temperature, whereas a RSS profile has a ramp up to soak that looks like a "plateau" and is then followed by a spike to the peak temperature.

Using the baseline profile, prediction software allows us to redefine a desired process window, which will be the target in further optimization steps. This is an iterative process where a prediction of new oven settings will be made, input into the oven, equilibrated, and then re-measured by sending the profiler and profiling board through the oven again. The new profile may then be further tweaked to get even closer to the desired process window.

The prediction software calculates a process window index or PWI. The PWI displays where the profile lies within the process window limits. If the profile is not within acceptable limits then the program suggests changes for the oven settings using a predictor. This process can be continued until a good profile has been achieved.

SAC alloys have been the de-facto choice of solder alloy for SMT in a variety of different applications in the electronics industry[1]. In this study, profiles were developed for each alloy based on unique process window specifications. Each of these alloys was then dropped into several different profiles to see how much the solder joints differed after reflow.

Once test boards were assembled, several areas were considered to see the impact of different profiles. Components in these areas included passives, SOTs, QFNs, and D-Paks.

EXPERIMENTAL DESIGN:

Materials:

Solder paste was at room temperature. All solder pastes have ROL0 halogen-free no-clean flux vehicles as noted in Table 1.

Equipment:

- Commercially available printer
- 100µm-thick 100% laser cut and electro-polished with nano-coating
- Commercially available SPI
- Commercially available pick and place
- Commercially available reflow oven

Components:

- 0402 capacitors and resistors
- 0201 capacitors and resistors
- 1206 capacitors and resistors
- D2PAK
- SOT-23
- DR MLF156

Reflow Profiling Process:

The profiles developed for this experiment were derived from the SAC305 baseline profile. All profiles were measured using a fully-populated board, as shown in Figure 1. The thermocouples were attached to the board using the aluminum tape and reinforced with Kapton tape.

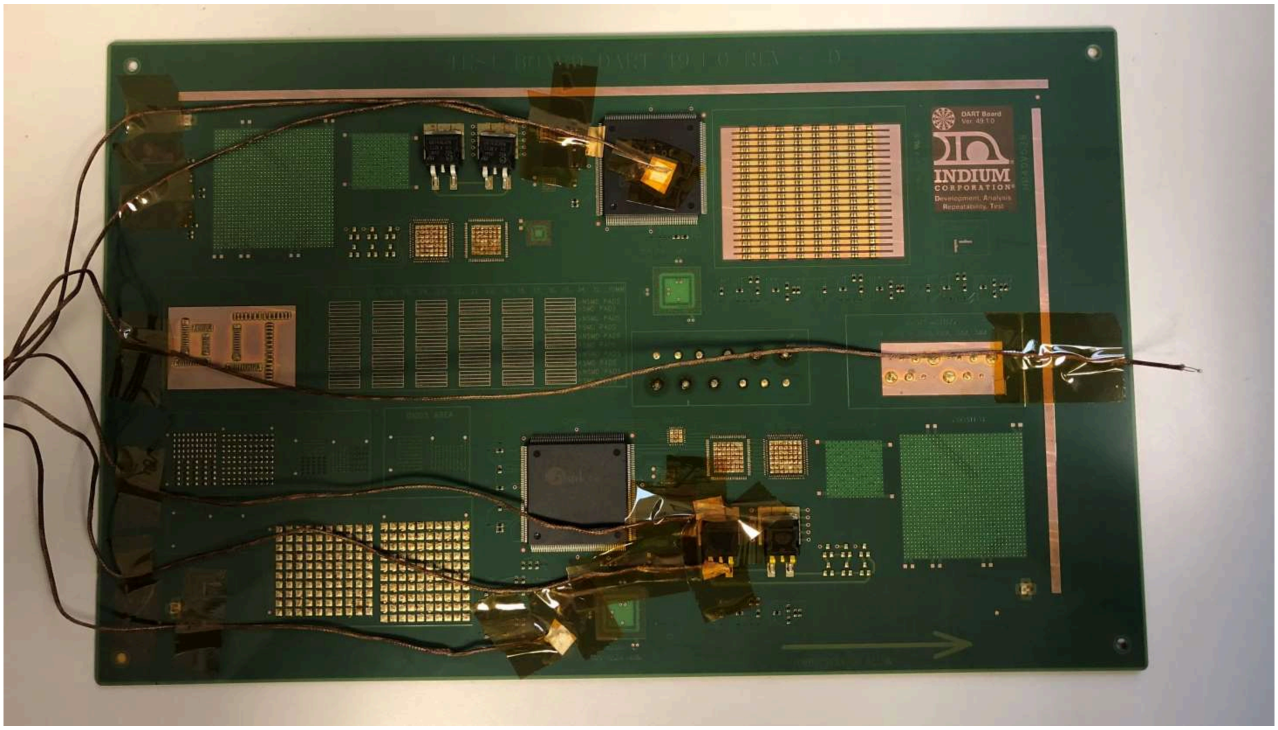

Figure 1. Test board with thermocouples affixed for profiling.

Table 2. Reflow profiling summary table.

	Profile Window Settings									Avg. Profiling Result				
	Max Rising Slope (deg C/s)		Soak Time (s)		Peak Temp (deg C)		Time Above (s)							
Profile Ref:	Low	High	Low	High	Low	High	Temp (deg C)	Low	High	Max Rising Slope (deg C/s)	Soak Time (s)	Peak Temp (degC)	Time Above (s)	Liquidus (deg C)
Low	0	2	0	60	190	205	187	120	200	1.1	53.5	201.5	152.6	187
Mid	0.5	2	-	-	220	230	205	30	90	1.8	0.0	224.4	62.4	205
Baseline	0.5	2	-	-	235	245	220	30	90	1.9	0.0	242.4	82.4	220
RTP	0.5	2	-	-	240	250	226	30	90	1.7	0.0	244.3	61.6	226
RSS	0.5	2	50	90	240	250	226	30	90	1.7	56.5	244.1	76.9	226

The thermocouples were then plugged into the reflow profiler and the profiler was enclosed in the protective case. The first profile was a baseline, and served as a foundation for further profiles to be developed by changing the process window settings. Once the predictor software suggested new oven settings, these were updated and a new profile was collected by sending the board and profiler through the oven again.

Table 2 shows the profile window settings used for profile development with the prediction software as well as results for the target parameters. Full profiles, complete with PWI values can be found in the appendix. It should be noted that the profiling board included a thermocouple placed on top of a QFP to illustrate how a misplaced reading will affect the profile and resulting PWIs. Because this was intentionally not the best practice, corresponding readings for TC2 were not included in the summary in Table 2.

Table 3. Test matrix for alloys and profiles

Solder Paste	**SAC305**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										
Solder Paste	**Alloy A**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										
Solder Paste	**Alloy B**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										
Solder Paste	**Alloy D**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										
Solder Paste	**Alloy E**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										
Solder Paste	**Alloy F**									
Reflow Profile	Baseline		RTP		RSS		Mid		Low	
Run Number	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Check										

Procedure for Test Board Assembly:

The stencil printer was set-up to print test boards at 100mm/s and a pressure sufficient for the chosen squeegee size. Dummy boards were used for set-up and before OSP test boards were used, a wet/dry/vac stencil underside cleaning cycle was completed. Print quality was monitored to ensure consistency but will not be reported in this study.

Components were then placed on each board to be reflowed. Boards were then reflowed with various profiles according to Table 3.

RESULTS AND ANALYSIS:

In order to see the differences between profiles and alloys, all the test boards were analyzed by microscope and X-ray. This section will focus only on notable differences due either to profile or alloy.

Figure 2 shows several areas with SOTs. Generally, there was no variation in these solder joints. A good result shows proper wetting along all of the leads. The different alloys display good wetting for all profiles.

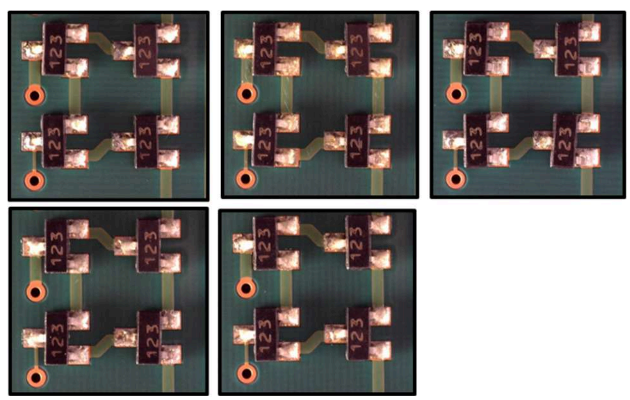

Figure 2. SOT23s with SAC305, Alloy D, Alloy B, Alloy E and Alloy F

A variety of passives was considered, including resistors and capacitors in 0201, 0402, and 1206 sizes. No tombstones were observed. Figure 3 shows a representative image of one of these sections. Visual analysis allows for verification of good fillet formation and tombstoning occurrences, but is a challenging way to identify solder beading, which requires high magnification and potentially a tilted viewing angle (see example in Figure 4).

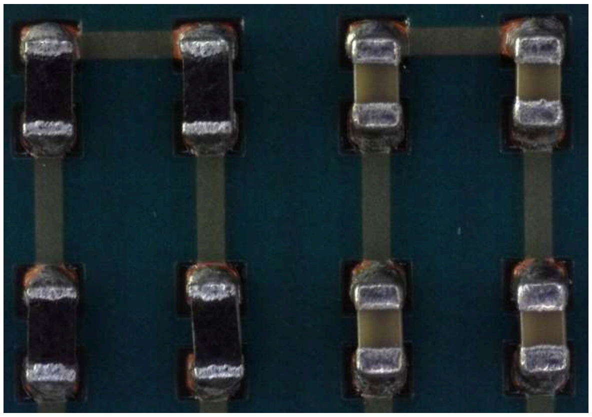

Figure 3: 0201 resistors and capacitors SAC305, mid profile

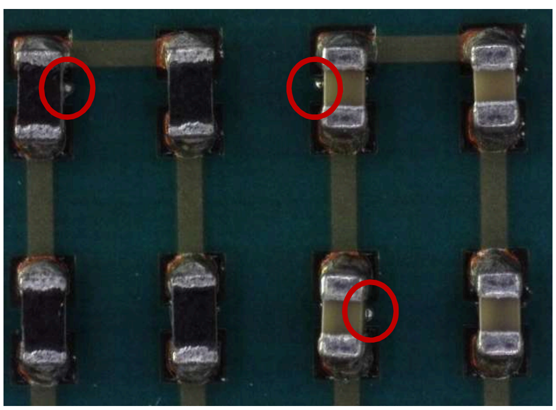

Figure 4: 0201 resistors and capacitors, SAC305, RSS profile

Looking at the same areas with X-ray, a larger area can be analyzed and solder beads can be identified more quickly. Figure 5 shows such an example. Solder beading is primarily dependent on stencil design, but reflow profile is often a first step as it is easier to modify. A critical factor is wetting and how easily solder beads are able to break-off and migrate along the side of the component. Sometimes a lower profile shows less propensity as in the comparison of Figures 3 and 4. Fewer solder beads with a RTP vs. the baseline profile can be found when comparing Figures 5 and 6.

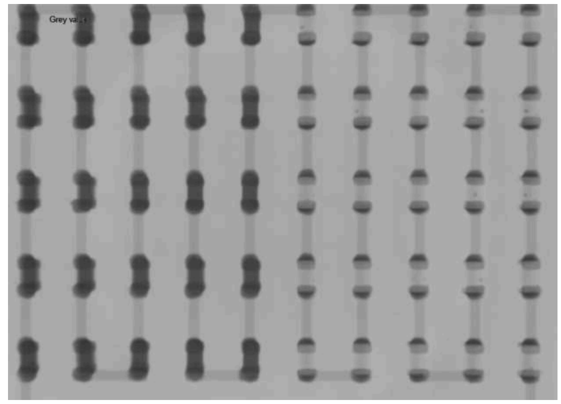

Figure 5: 0201 resistors and capacitors with Alloy D

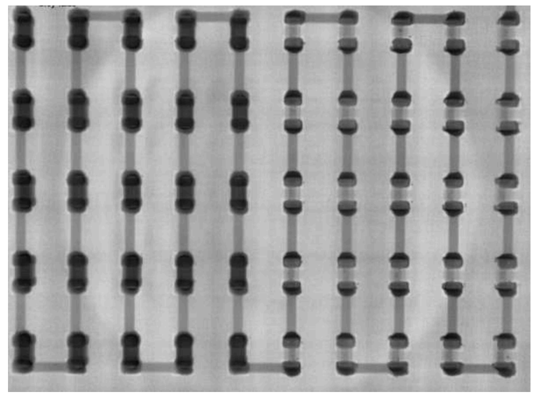

Figure 6: 0201 resistors and capacitors with Alloy D, RTP profile

For QFN and D-Pak components, X-ray analysis is performed to check wetting to the leads and voiding comparison. Figure 7 shows a typical dual-row quad-flatpack no-lead component (DRQFN). This component was omitted from further analysis because voiding values showed little variation. Looking closer, there is also prominent bridging on the perimeter leads. This is a typical finding for this type of design—one with many plated through-hole vias and a window-paned stencil. This creates a solder starved condition where the solder will wet down into the vias and away from the solder joint during reflow. As this happens, voiding will be prominent and the surface tension of the alloy as it migrates down the vias will pull the component closer to the board, reducing standoff height and resulting in bridged IOs along the perimeter. In the X-ray analysis, dark areas can be de-selected to aid voiding analysis. This excludes the vias from analysis, but also limits the areas where voids are detected, leading to very consistent voiding computations.

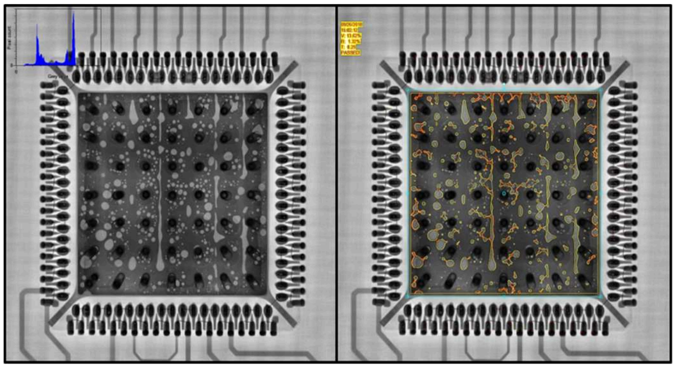

Figure 7: DRQFN with Alloy D, baseline profile

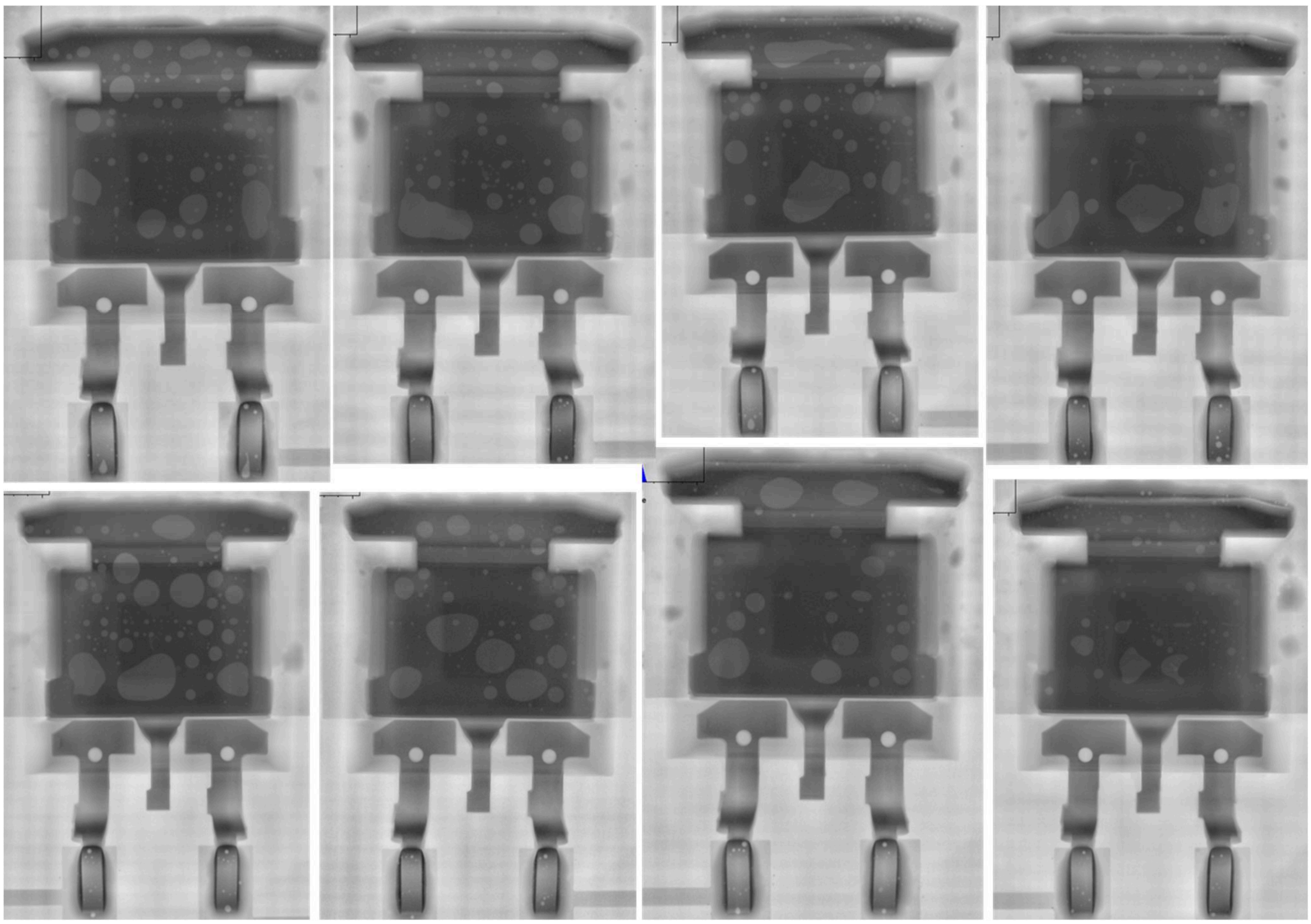

Figure 8: D-pak components in X-ray, SAC305 with the baseline profile

Figure 8 shows all of the D-pak components for SAC305 with the baseline profile. Due to the varying dark contrast for these components, numerical analysis was not achieved. Looking at the pictures, it is clear there would be a large range of variation within the data set, complicating any comparisons between alloys or profiles.

CONCLUSIONS:

The profiles developed in this study all showed very good results with the alloys tested. To demonstrate the appearance of poor soldering, a wider range of profiles would need to be tested. Visual inspection and X-ray are good for process control, maintaining the qualities attributed to reliable solder joints. In manufacturing, these qualities would ideally be aligned with process qualification boards that were exposed to further reliability testing.

Reflow profiling will continue to increase in importance as board material and component temperature limits stay the same and alloy melting points rise. Diligence and effort in reflow process development pays dividends with repeatability and first pass yield. Simply using one profile for many designs is not a luxury the electronics industry can continue to afford.

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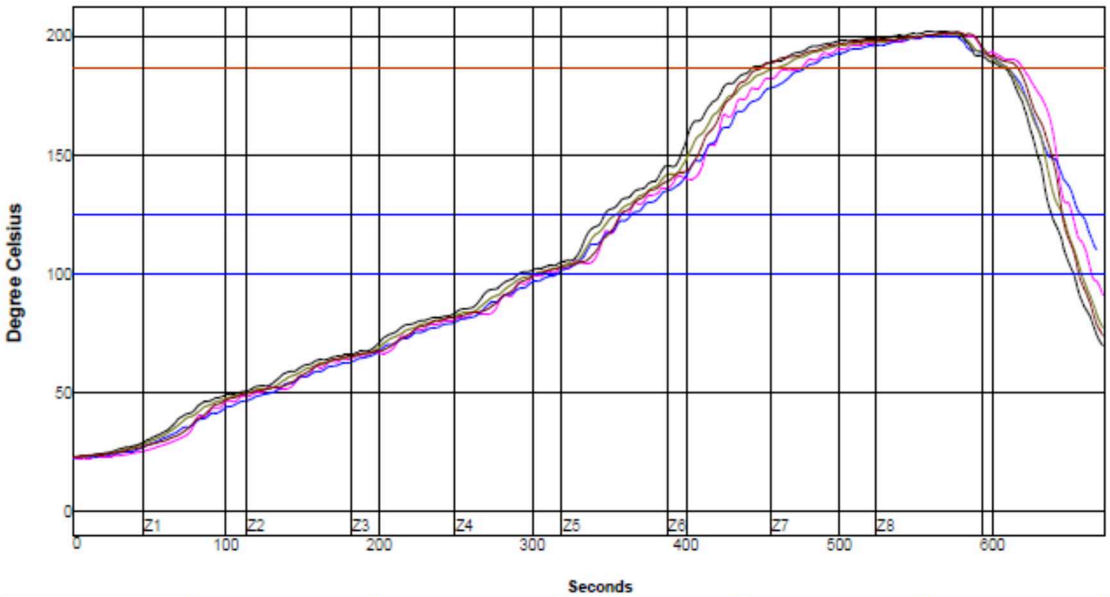
APPENDIX: REFLOW PROFILES

Low profile:

Setpoints (Degree Celsius)								
Zone	1	2	3	4	5	6	7	8
Top	50	65	79	102	140	194	201	205
Bottom	50	65	79	102	140	194	201	205
Conveyor Speed (inch/min):	11.3							



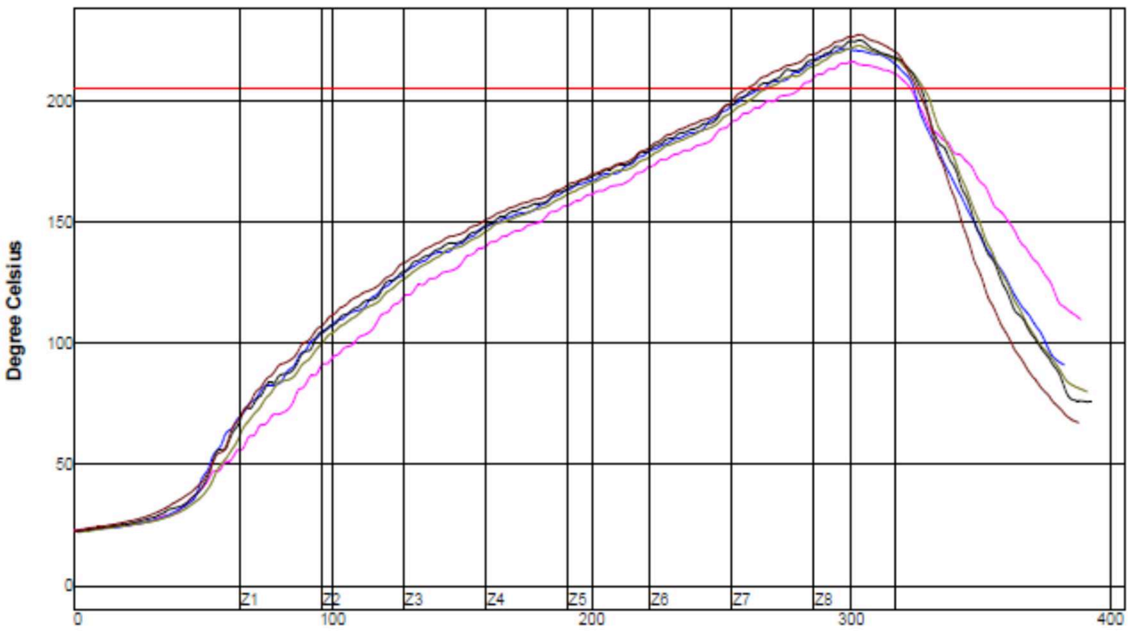
PWI= 88%	Max Rising Slope		Max Falling Slope		Soak Time 100-125°C		Peak Temp		Tot Time /187°C	
<TC2>	1.35	35%	-2.67	16%	49.95	66%	201.54	54%	143.97	-40%
<TC3>	0.85	-15%	-1.60	70%	48.46	62%	200.51	40%	131.03	-72%
<TC4>	1.07	7%	-2.24	38%	53.06	77%	201.22	50%	149.65	-26%
<TC5>	1.16	16%	-2.47	27%	56.37	88%	202.40	65%	162.94	7%
<TC6>	1.22	22%	-2.77	11%	56.12	87%	201.78	57%	166.77	17%
Delta	0.50		1.17		7.91		1.89		35.74	

Process Window:

Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 20 Seconds)	0.0	2.0	Degrees/Second
Max Falling Slope (Calculate Slope over 20 Seconds)	-5.0	-1.0	Degrees/Second
Soak Time 100-125°C	0	60	Seconds
Peak Temperature	190	205	Degree Celsius
Total Time Above - 187°C	120	200	Seconds

Mid Profile

Setpoints (Degree Celsius)								
Zone	1	2	3	4	5	6	7	8
Top	105	130	150	165	180	200	225	240
Bottom	105	130	150	165	180	200	225	240
Conveyor Speed (inch/min):	23.0							



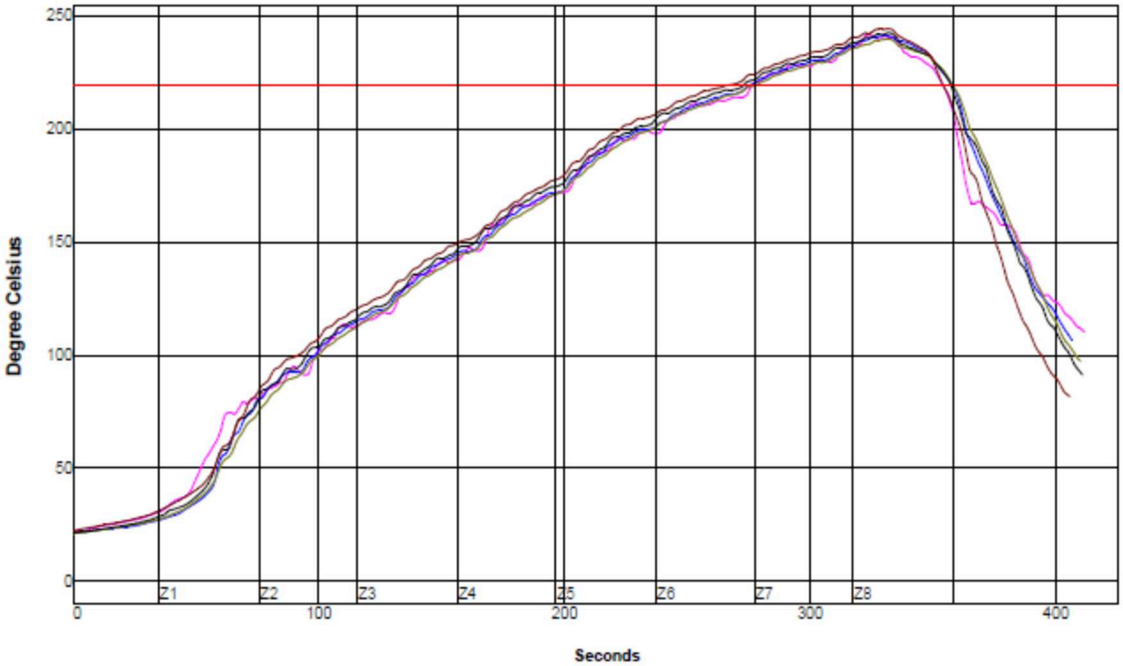
PWI= 171%	Max Rising Slope		Reflow Time /205°C		Peak Temp	
<TC2>	1.18	18%	43.11	-56%	216.43	-171%
<TC3>	1.85	85%	58.99	-3%	221.76	-65%
<TC4>	1.69	69%	61.13	4%	223.00	-40%
<TC5>	1.82	82%	63.25	11%	225.23	5%
<TC6>	1.80	80%	66.03	20%	227.65	53%
Delta	0.67		22.92		11.22	

Process Window:

Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 20 Seconds)	0.5	2.0	Degrees/Second
Time Above Reflow - 205°C	30	90	Seconds
Peak Temperature	220	230	Degree Celsius

Baseline Profile

Setpoints (Degree Celsius)								
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Top	110	130	155	185	215	225	240	255
Bottom	110	130	155	185	215	225	240	255
Conveyor Speed (inch/min): 21.0								



PWI= 104%	Max Rising Slope		Reflow Time /220°C		Peak Temp	
QFP Top	1.93	93%	77.41	58%	242.12	42%
QFP Lead	2.04	104%	81.02	70%	241.62	32%
DPAK Flat	1.71	71%	79.35	65%	240.12	2%
DPAK Lead	1.86	86%	84.19	81%	242.87	57%
Cap	1.91	91%	85.23	84%	244.67	93%
Delta	0.33		7.82		4.55	

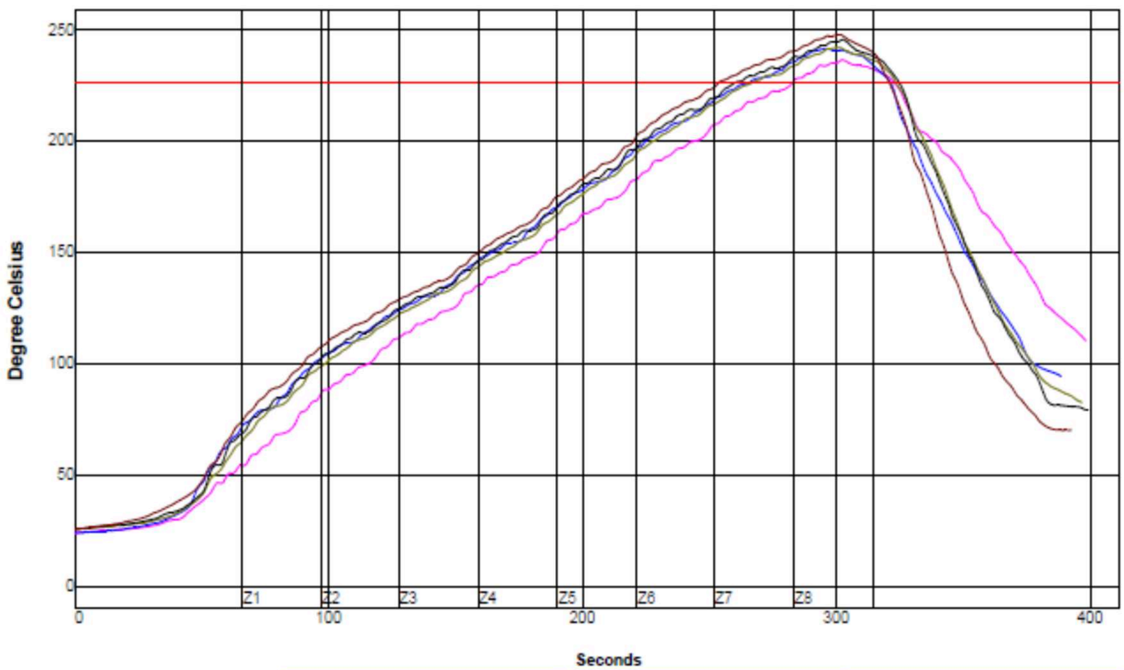
Process Window:

Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 20 Seconds)	0.5	2.0	Degrees/Second
Time Above Reflow - 220°C	30	90	Seconds
Peak Temperature	235	245	Degree Celsius

RTP Profile

Setpoints (Degree Celsius)								
Zone	1	2	3	4	5	6	7	8
Top	100	125	140	170	200	230	245	260
Bottom	100	125	140	170	200	230	245	260

Conveyor Speed (inch/min): 23.0



PWI= 171%	Max Rising Slope		Reflow Time /226°C		Peak Temp	
QFP Top	1.11	11%	40.37	-65%	236.43	-171%
QFP Lead	1.74	74%	56.14	-13%	241.67	-67%
DPAK Flat	1.49	49%	57.22	-9%	242.05	-59%
DPAK Lead	1.70	70%	65.40	18%	245.60	12%
Cap	1.68	68%	67.45	25%	247.90	58%
Delta	0.63		27.08		11.47	

Process Window:

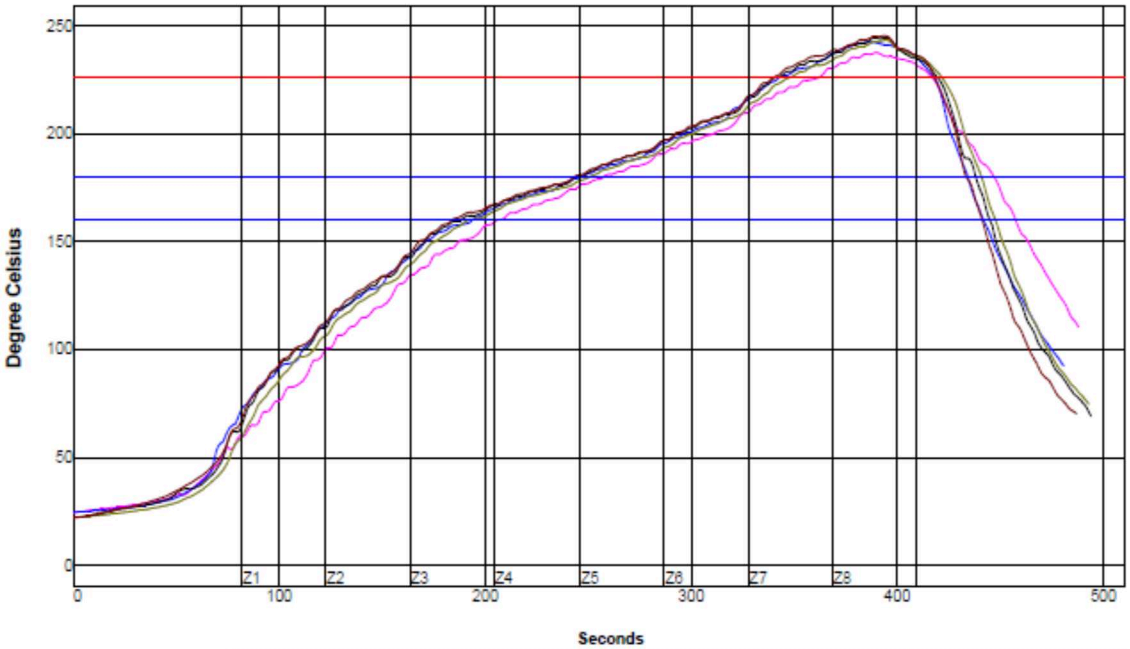
Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 20 Seconds)	0.5	2.0	Degrees/Second
Time Above Reflow - 226°C	30	90	Seconds
Peak Temperature	240	250	Degree Celsius

RSS Profile

Setpoints (Degree Celsius)

Zone	1	2	3	4	5	6	7	8
Top	110	140	170	180	195	215	245	255
Bottom	110	140	170	180	195	215	245	255

Conveyor Speed (inch/min): 18.0



PWI= 147%	Max Rising Slope		Soak Time 160-180°C		Reflow Time /226°C		Peak Temp	
QFP Top	1.17	17%	51.84	-91%	55.55	-15%	237.67	-147%
QFP Lead	1.75	75%	52.51	-87%	75.50	52%	242.66	-47%
DPAK Flat	1.68	68%	58.93	-55%	74.17	47%	243.50	-30%
DPAK Lead	1.80	80%	55.49	-73%	79.58	65%	244.73	-5%
Cap	1.71	71%	59.18	-54%	78.46	62%	245.56	11%
Delta	0.63		7.34		24.03		7.89	

Process Window:

Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 20 Seconds)	0.5	2.0	Degrees/Second
Soak Time 160-180°C	50	90	Seconds
Time Above Reflow - 226°C	30	90	Seconds
Peak Temperature	240	250	Degree Celsius