Novel Thermally Conductive Low Pressure Overmold Materials as a Solution for Thermal Management

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ABSTRACT

The dissipation of heat from a power die, such as those used to drive the increasingly popular LED arrays, has traditionally been achieved by use of a thermal interface material (TIM) and a metallic heat sink. The performance of this system is usually limited by the capability of the TIM portion of the layers. In circumstances where the unit may be open to the environment, an additional housing is required which can further degrade the thermal performance of the system.

By replacing the TIM, heat sink and protective housing with a single thermally conductive, protective thermoplastic overmold material, system performance can be maintained and the assembly process streamlined. In this paper, the processing and performance of such materials will be discussed.

The isotropic nature of these materials allows heat dissipation not only in the vertical direction as with a traditional system, but also laterally, thus reducing hot spots and enhancing overall performance. Thermal models show that even a modest thermal conductivity (0.5 $W(mK)^{-1}$) can reduce hot spots by over 30ºC compared to a regular low pressure molding (LPM) material.

These materials retain the low melt viscosities typical of LPM materials and can easily be molded into a wide variety of shapes, allowing flexibility in the final form of the product.

Key words: Thermal management, Low pressure molding

INTRODUCTION

In today's competitive environment, the total cost of ownership is becoming an increasingly important parameter versus the total cost of a material. The ability to save time, equipment use and labor must all be factored into the total cost equation. In addition, materials can bring multiple efficiency-enhancing benefits to the final product in order to reduce the bill of materials (BOM) and processing steps.

With the reduction in size and increase in functionality of modern electronics devices, thermal management has become increasingly important. Historically, there have been many different approaches to the management of heat transfer and heat flow within a PCB assembly --from metal sintering, thermal pastes, potting solutions and removal of air gap materials to more recent methods such as reduced thermal impedance and phase change products. All of these materials share a common feature in that they channel the heat from its source to a heat sink or heat spreader, where the heat is then radiated away.

In parallel, the desire to have multifunctional materials that minimize the number of manufacturing steps has pushed the development of materials that can perform several functions simultaneously for the overall assembly. These functions may include thermal conductivity and environmental protection, for example.

This allows the manufacturer to use a single material, reducing the number of line items in the BOM as well as eliminating manufacturing steps. In some cases, the replacement material may not be optimized for the environment in which it will be used, but the multifunctional benefits offset the limitation in performance.

Low Pressure Molding (LPM) has been successfully used for many years as a method of post-assembly PCB encapsulation and environmental protection. The advantage of this technology is that it allows enhanced design flexibility for the final form of the device. Recently, efforts have been made to expand the functionality of LPM materials beyond their traditional environmental protection. Alterations to the base material, however, must be carefully controlled so as not to negatively impact material processing.

Historically, LPM materials have been low melt viscosity resins of 1000 to 10000 mPa·s allowing for gravity feed systems. These materials have also been unfilled and, as such, produce negligible wear and tear on the processing equipment. However, these materials are effectively thermally insulating (typical thermal conductivity of 0.15 $W(mK)^{-1}$ due to the polymer resin and lack of filler.

One way to enhance the functionality of these materials, is by the addition of fillers that can be added to produce the desired performance characteristics. The selection and amount of the fillers to be incorporated is dependent upon the desired material properties.

In this case, a variety of thermally conductive materials were used. The addition of fillers may be reasonably expected to impact the processing of the material in multiple ways. However, by careful selection of additives, the effects can be limited and result in minimal impact on processing and/or equipment.

The addition of fillers to the base resin system will change the viscosity, thermal stability, etc., of the material, all of which will need to be accounted for in processing.

In this study, three LPM materials were evaluated; one thermally insulating, and two thermally conductive materials formulated with varying levels of thermal conductivity. The base material properties were measured to determine the impact of the filler additions.

After the material is characterized, the properties will be used to develop a thermal model which will then be utilized to calculate expected skin temperatures for a test vehicle. Finally, the materials will be used to overmold a power die and build the test vehicle. The performance will then be measured and compared to the model.

EXPERIMENTAL METHODS

Model Parameters and Constraints: A commercially available IGBT was used as the heat source for the thermal model and functional testing. The model used the IGBT as the heat generating component. The model utilized an overmold thickness of 3 mm around the sides and bottom with the top exposed.

An aluminium cooling plate was placed below the overmolded IGBT to control the direction of the model's heat flow. The simulation was then run using the following parameters: 3W of power, 60°C copper cooling plate and a 3 mm thick overmold material around the IGBT.

The model was run using 3 varying levels of thermal conductivities: 0.2, 0.6 and 1.5 $W(mK)^{-1}$. The model output was a thermal map showing the thermal gradient and skin temperature of the assembly under the above constraints and parameters.

Material Characterization: The thermal model only evaluated the change in the thermal performance of an assembly. However, the actual effects on material properties must also be evaluated. Two of the most important properties for a LPM material are adhesion and viscosity, which both affect the environmental protection ability and the processing parameters of the material.

Viscosity was measured using a parallel plate method and was determined across the expected processing temperature range using a production Rheometric Expansion System. Adhesion was measured using a modified ASTM 1002 test method lap shear. Parts were molded using an automated single station low pressure moulding machine with the following settings: melt pot temperature of 225°C with material injected at 250 psi for 30 s, followed by 10 s of cooling. The coupons were 4″ x 1″ solder masked FR4 with a ½″ x 1″ overlap. The bond line was controlled at 3 mm(see figure 1 below).

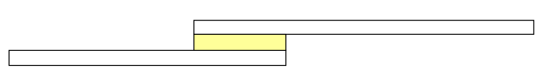

Figure 1: Lap shear test assembly

The molded joints were allowed to sit for 24 hrs. after molding and before testing to allow residual molding stress to relax. The joints were pulled at 1.27 mm/min.

Functional Test Vehicle: The same IGBT used for the thermal model was then used for a functional test assembly to compare with the simulation. The IGBT was molded using two materials: with 0.2 and 0.6 $W(mK)^{-1}$ (see figure 2 below).

Again, the low pressure moulding machine was used along with an appropriate mold with varying thickness. The samples were then tested in a custom sample holder using a heating current of 36A for 20 seconds, followed by 2000 seconds of cooling. The output of this testing was the thermal resistance versus time plots showing the thermal response of the assembly.

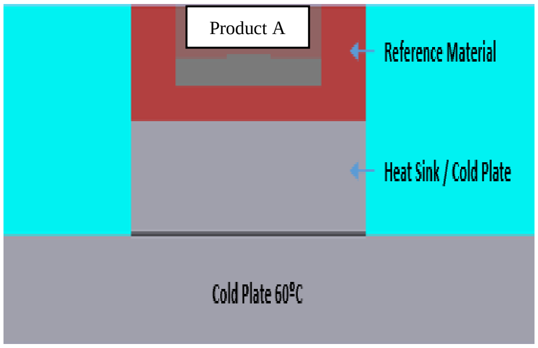

Figure 2: Model Experimental Model Setup

RESULTS

Thermal model analysis of the standard resin yielded results that confirm and prove the thermal insulating characteristics of the standard unfilled resin systems. The model shows that the IGBT runs excessively hot at nearly 150°C, with the overmold material running up to 105°C in the bulk with surface temperatures in the 60°C-90°C range, as seen in Figure 3.

These results also indicate that the LPM material is acting as a thermal insulator with the overmold material actively maintaining the heat around the IGBT heat source. This is the red area in the centre of Figure 3 below.

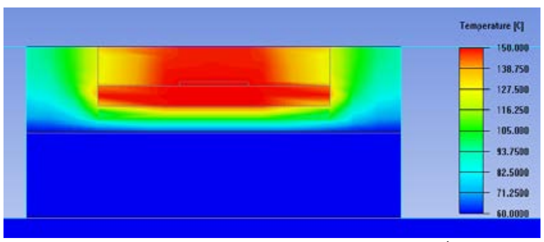

Figure 3: Thermal model of 0.2 W(mK)$^{-1}$ immediately after power cycle.

The second and third simulations are based on materials that have bulk thermal conductivities of 0.6 and 1.5 W(mK)$^{-1}$ respectively. The 0.6 W(mK)$^{-}$1 is at the low end of what may be considered thermally conductive with respect to thermal management applications. The impact of the step up in thermal conductivity is significant, as illustrated by the model.

The IGBT junction temperature is decreased from 150°C down to 80°C at 0.6 W(mK)$^{-1}$ (see figure 4). Further increasing the thermal conductivity to 1.5 W(mK)$^{-1}$ results in a modest 10°C temperature reduction, bringing the junction temperature down to 70°C (see figure 5). The surface of the assembly realizes a concomitant improvement in temperature down to 70°C and 60°C, respectively, under the same power conditions.

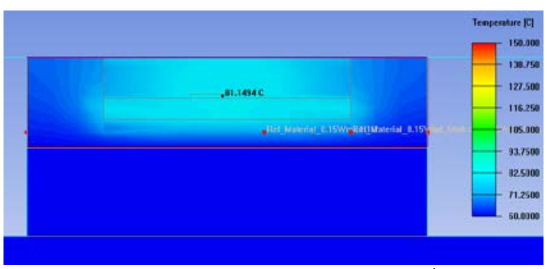

Figure 4: Thermal model of .6 W(mK)$^{-1}$ immediately after power cycle

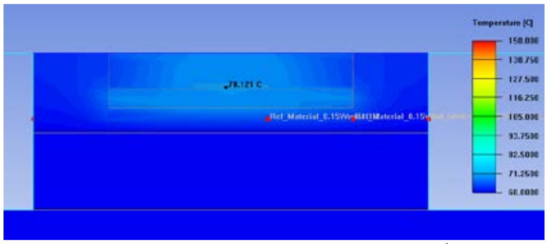

Figure 5: Thermal model of 1.5 W(mK)$^{-1}$ immediately after power cycle

The simulations show a significant improvement in thermal management of the overall device. This allows the part to run at higher power levels without compromising the efficiency of the part or the material performance.

Even though the model shows that the material will be a significant improvement over the standard unfilled resin systems and has potential in these types of applications, it does not address the impact of the filler on the molding process or other performance characteristics.

A critical property for processing is melt viscosity, as this will determine if the material is suitable for LPM. Using a standard parallel plate method, the viscosity profile of the standard resin and a 0.5 W(mK)$^{-1}$ resin were run and plotted together to allow easy comparison. The data shows that the resin system is resilient to the introduction of the desired filler system and that limited levels of thermal conductivity can be achieved without substantially changing the viscosity of the system.

At traditional molding molding temperatures of 210°C, the viscosity rises from ~3000 mPa·s for the standard LPM resin to around ~7500 mPa·s (see figure 6 below) for the thermally conductive filled resin. At this viscosity, the filled system still falls within the standard viscosity range for low pressure molding material solutions.

The importance of viscosity is that it determines the molding pressure and flow characteristics of the material. In practical terms, the viscosity increase associated with the addition of the filler will require a small modification to the molding parameters, but are still within the capability of standard molding equipment.

The addition of fillers to resin also raises concerns about filler settlement during prolonged periods at elevated temperatures. A preliminary study of the density of the material after 8 hours at 210°C in a glass jar showed no visible signs of settlement. An extended 24 hr. aging study in an aluminium syringe showed a minor change in density from ~1.73 g/cm^3 to ~2g/cm^3 at the bottom of the container.

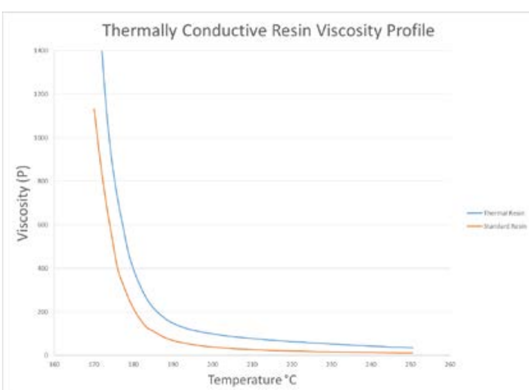

Figure 6: Viscosity comparison between standard LPM resin and thermally conductive resin.

When evaluating a new encapsulation/circuit board protection material, a key property is the adhesion to the substrate, which determines its viability and the type of environments in which it can be used. To determine the adhesion of the new thermally conductive filled resin, a modified ASTM 1002 lap shear was used and the results compared with two standard unfilled resins: resin1 being the base resin to which the filler was added.

A comparison of the adhesion break loads is shown in figure 7 below. The addition of the thermal filler to the resin system has no negative impact on the adhesion strength of the material, and may even result in improved adhesion compared with other LPM resin materials.

The significance of the retention of adhesion strength is that the material can continue to be used as an effective environmental protection encapsulant material, while also providing thermal dissipation benefits.

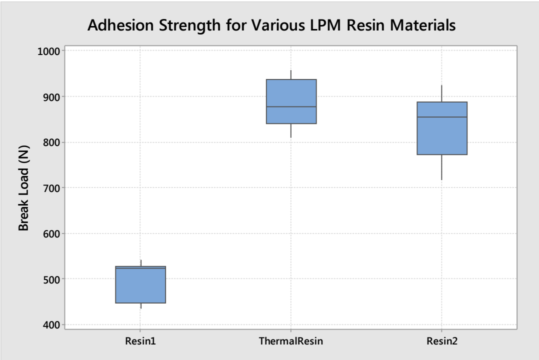

Figure 7: Chart comparing adhesion strengths of various LPM resins.

While the material model and initial material property testing show that the material would be a good choice for use as a thermally conductive overmold material, further validation through functional thermal testing is required. To facilitate this, the initial thermal model was used to generate a test vehicle to compare with the model.

The IGBT was overmolded with the thermal material (0.6 $W(mK)^{-1}$) and a standard resin (0.2 $W(mK)^{-1}$), and put through a power cycle and allowed to cool. This differs slightly from the model conditions in that the model was held at a constant 3W while the functional test was performed at 36A, which resulted in higher operating temperatures.

While the part was cooling down, the thermal resistance was measured and plotted versus time for each of the materials. What can be observed is a significant difference in the thermal resistance of the assembly after the power cycle.

The difference in thermal resistance (Z^{th}) between the two materials was approximately 2 KW^{-1}. This equates to an operating temperature difference of 38°C, which is calculated by multiplying the power (in this case 21W) by the difference in thermal resistance Z^{th}, which was ~1.8 (see Figure 8).

This difference, although substantial, is only ≈55% of the expected difference (70°C) based on the thermal model. The variance can be explained, at least in part, by the model assuming a zero interfacial resistance between the overmold and the substrate. The difference in power put through the device was also a factor and resulted in high operating temperatures near the material melt point.

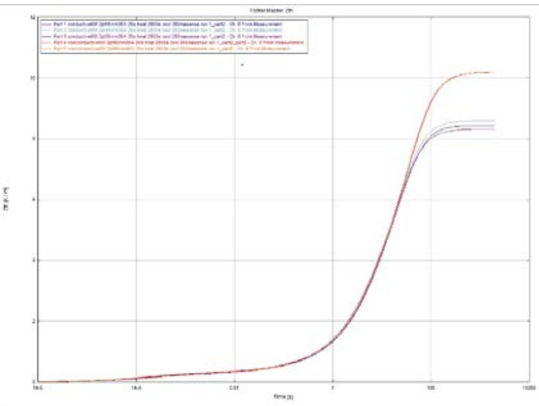
Figure 8: Thermal resistance comparison between filled and unfilled resin systems.

Conclusions

This study has identified the opportunity to replace some traditional thermal management solutions with a multifunctional, low pressure overmold material. The performance of a thermally conductive low pressure molding resin was compared with a traditional thermally insulating material across a range of properties. Thermal modelling laid the ground work by predicting the potential for significant operating temperature reductions (up to 70°C) with a modest increase in thermal conductivity.

Practical material evaluation showed that the desired increases in thermal conductivity could be achieved without compromising the material properties deemed critical for maintaining material functionality and processing with currently available equipment.

Adhesion and viscosity were both maintained within acceptable limits and, in some cases, were comparable to the standard resin, while the thermal conductivity was increased from 0.2 $W(mK)^{-1}$ to 0.6 $W(mK)^{-1}$. Finally, a functional test was performed on a thermal test piece using the two resins.

This test showed that the material can achieve up to a 38°C reduction in junction temperature for the same assembly at the same power settings during the functional testing. This data suggests that thermally conductive overmolding materials can be used as a form of thermal management, while simultaneously providing effective circuit board protection.

Acknowledgements
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Thermal Profile Variation and PCB Reliability

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Thermal Profile Variation and PCB Reliability

- **Introduction**
- Methodology
- Results
- Conclusion

Introduction

- When designing PCBs, solder paste selection is critical
  - After paste type and supplier are identified, the manufacturing process is developed
  - Correct thermal profile results in good solder joint quality
- In accordance with J-STD-004/005 (IPC TM-650)
  - At a minimum, recommended thermal profile should produce passing corrosion, SIR and electrochemical migration results

Introduction

- As PCB surface density and component mass increases, is the recommended thermal profile sufficient to produce quality solder bonds and fully volatilize flux residues?
- Residues that are ionic in nature, they can lead to failure mechanisms
  - Leakage current
  - Electrochemical migration
  - Dendritic growth

Introduction

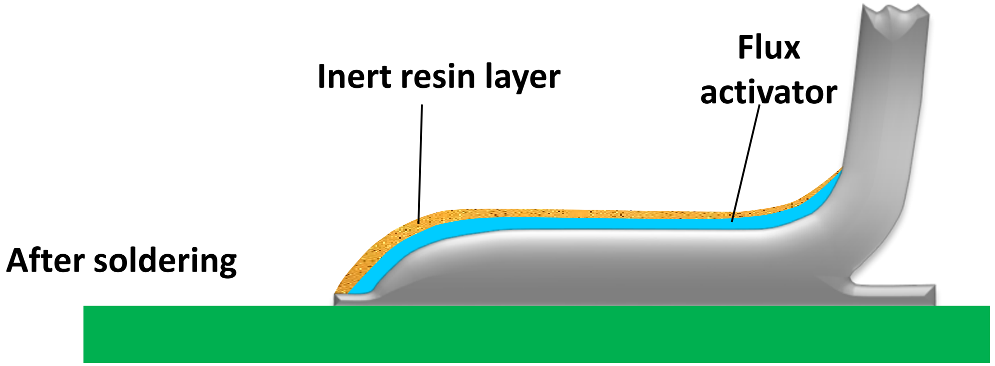
- Reflow optimization challenges due to:
  - High lead-free temperatures
  - Smaller print deposits
  - Board size and density (thermally massive)
  - Temperature sensitive components (Al and polymer capacitors, inductors, LEDs, transformers, fuses etc.)

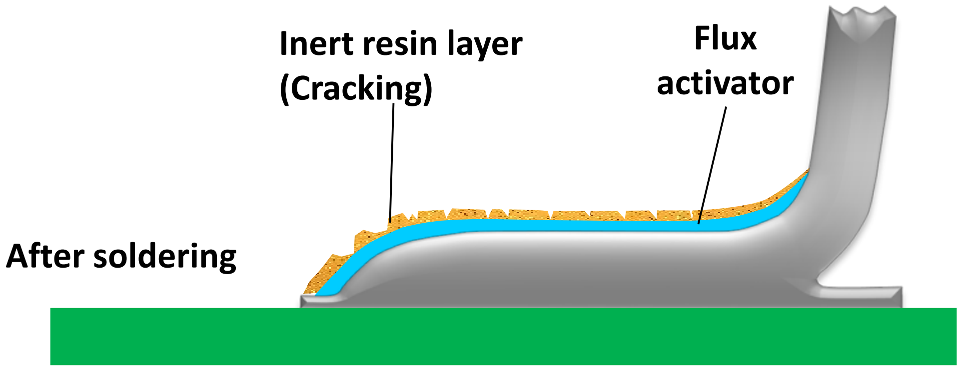
Introduction

- With OA or RMA solder pastes, activators will be cleaned following reflow eliminating negative impact
- With No-Clean solder paste when boards are not cleaned, reliability can be impacted

Introduction

- Climatic stress can cause cracking of the resin layer exposing flux activators
  - This can cause contamination induced leakage current, electrochemical migration and dendritic growth
- Cleaning No-Clean solder paste residues following reflow can ensure assembly reliability



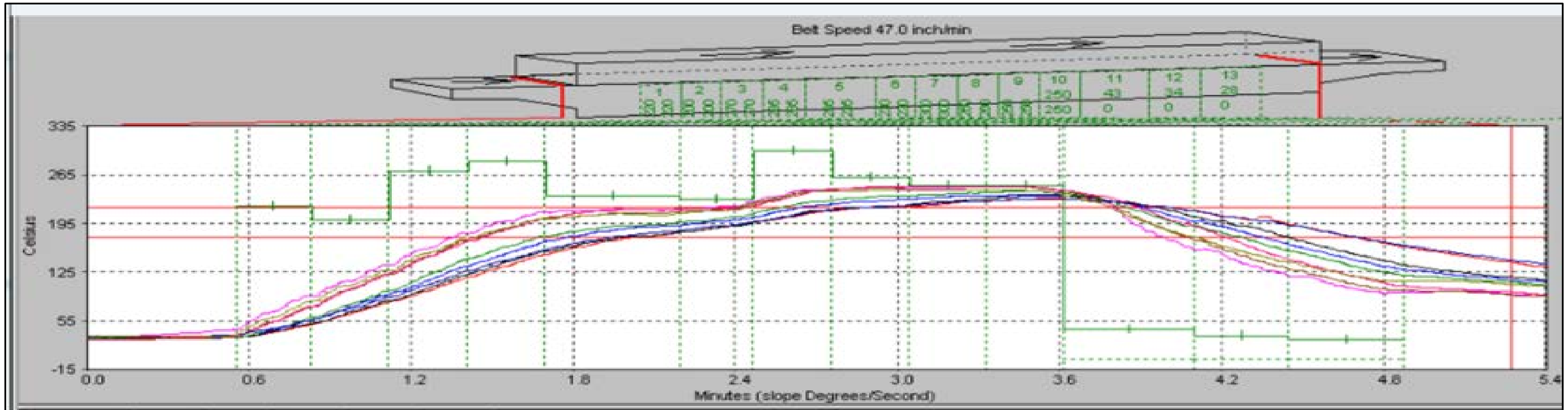


Introduction

- Surface temperature variation on the PCB is inevitable due to:
  - Component density increase
  - Thermal mass variation increase

Introduction

Example thermal profile of a highly dense assembly:



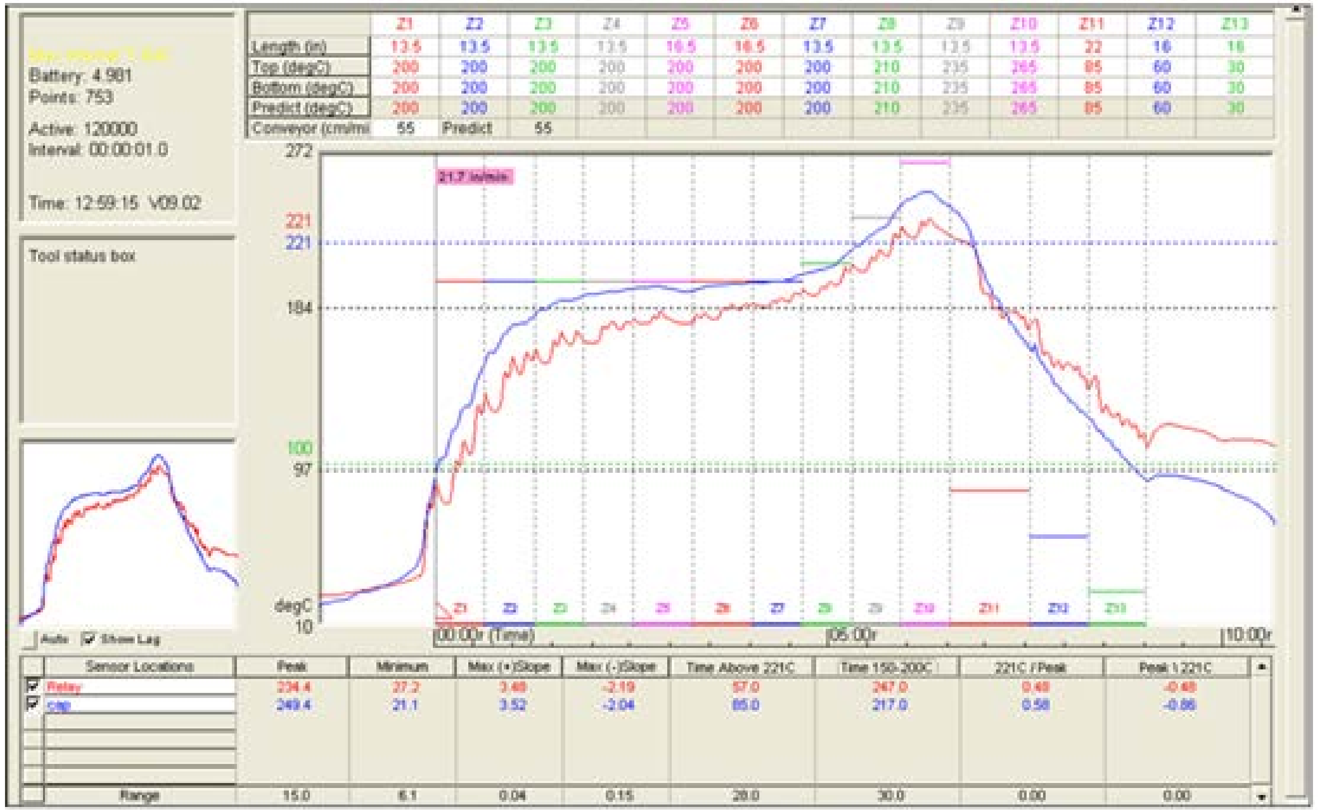
	Peak	Max Rising Slope	Max Falling Slope	Rising Time Between 175/217	Total Time Above 217
1	246.0	3.04	-3.66	55.87	90.87
2	236.8	2.41	-1.84	51.01	77.23
3	230.2	2.09	-1.67	49.78	69.39
4	234.6	2.30	-1.80	49.25	70.38
5	240.5	2.76	-2.16	53.57	77.60
6	247.8	2.94	-3.09	55.99	85.67
7	248.8	2.81	-2.44	57.63	88.39
8	230.8	2.23	-1.25	54.26	70.50
9	243.3	2.91	-2.53	59.28	81.76
TC Mean	239.9	2.61	-2.27	54.07	79.09
TC Range	18.6	0.95	2.41	10.03	21.48

Max peak temp: 250°C

Temperature variation: Up to 18°C

Introduction

Example thermal profile of a highly dense assembly:



Max peak temp: 250°C

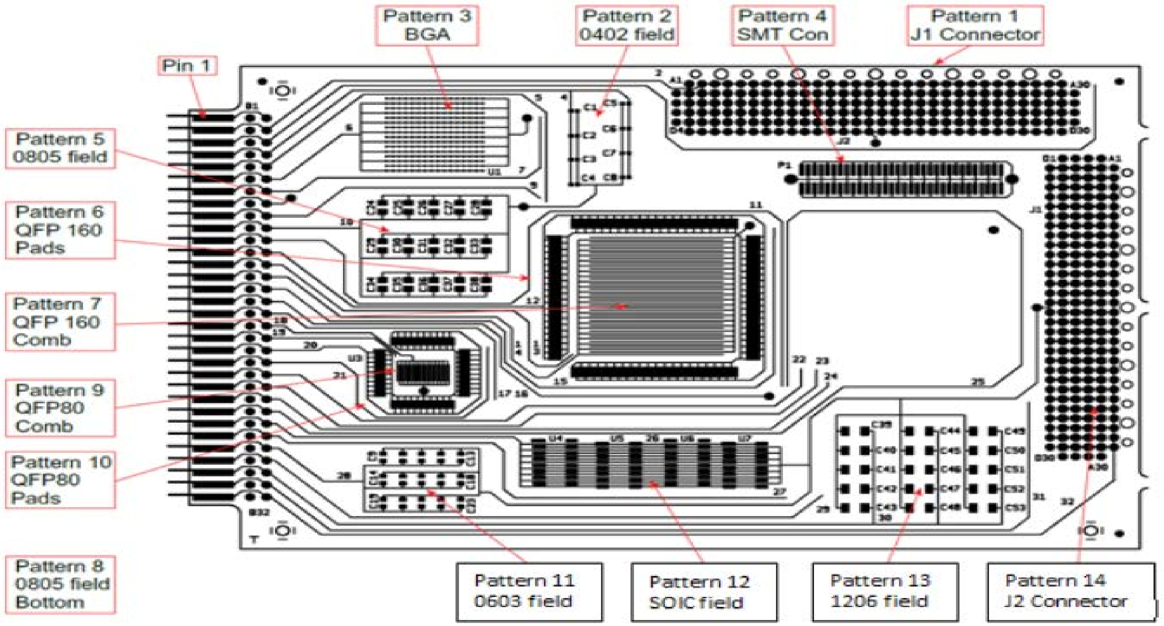
Temperature variation: Up to 15°C

Introduction

- Purpose of the technical study to:
  - Evaluate the effect of temperature variation on assembly reliability focusing on No-Clean solder pastes
  - Investigate if ionic activators may be left behind when the peak temperature is not realized and thermal variations exist
  - Determine whether SIR values will get impacted
  - Determine if post solder cleaning improves SIR values

Introduction

- IPC-B-52 test vehicle was used
  - Reduced the recommended peak leaded and lead-free temperature by 10^{o}C and 15^{o}C each
  - Evaluate its effect on surface temperature and subsequent SIR test



Thermal Profile Variation and PCB Reliability

- Introduction
- **Methodology**
- Results
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Methodology

- Six (6) No-Clean solder pastes were used

No-Clean Solder Paste Types	
Lead-free	Paste A
	Paste B
	Paste C
Leaded	Paste D
	Paste E
	Paste F

Methodology

- Three (3) test vehicles were prepared for each paste
  - Reflowed at manufacturers recommended profile
  - Two additional reflow profiles targeting 10^{o}C and 15^{o}C lower peak temperatures
  - Targeting above peak temperature not considered assuming temperature sensitive components exist

Methodology

- Thirty (30) test vehicles were employed
  - Five (5) process conditions were evaluated for each paste

Process Conditions		
1	Recommended ramp reflow profile	Not Cleaned
2	Ramp reflow profile variation (-10°C peak)	Not Cleaned
3	Ramp reflow profile variation (-10°C peak)	Cleaned
4	Ramp reflow profile variation (-15°C peak)	Not Cleaned
5	Ramp reflow profile variation (-15°C peak)	Cleaned

Methodology

Recommended Leaded Reflow Oven Settings (°C)											
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Cooling
Top	90	100	130	150	160	170	180	190	210	235	3 Zones
Bottom	90	100	130	150	160	170	180	190	210	235	3 Zones
	Fan Speed at 50%							Fan Speed at 60%			

Recommended Lead-free Reflow Oven Settings (°C)											
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Cooling
Top	100	120	150	180	190	200	210	230	245	255	3 Zones
Bottom	100	120	150	180	190	200	210	230	245	255	3 Zones
	Fan Speed at 50%							Fan Speed at 60%			

Methodology

Cleaning Equipment Operating Parameters	Equipment type	Spray-in-Air Inline
	Cleaning Agent	Aqueous based Cleaning Agent
	Concentration	15%
	Conveyor Belt Speed	1 ft/min
	Pre-wash Pressure (Top/Bottom)	50 PSI / 40 PSI
	Wash Pressure (Top/Bottom)	80 PSI / 70 PSI
	Wash Hurricane Pressure (Top/Bottom)	40 PSI / 40 PSI
	Cleaning Temperature	150°F
Rinse	Rinsing Agent	DI-water
	Rinse Pressure (Top/Bottom)	80 PSI / 70 PSI
	Rinse Hurricane Pressure (Top/Bottom)	40 PSI / 40 PSI
	Rinsing Temperature	150°F
	Final Rinse Pressure (Top/Bottom)	30 PSI / 20 PSI
	Final Rinse Temperature	Room Temperature
Drying	Drying Method	Hot Circulated Air
	Drying Temperature	160°F-190°F

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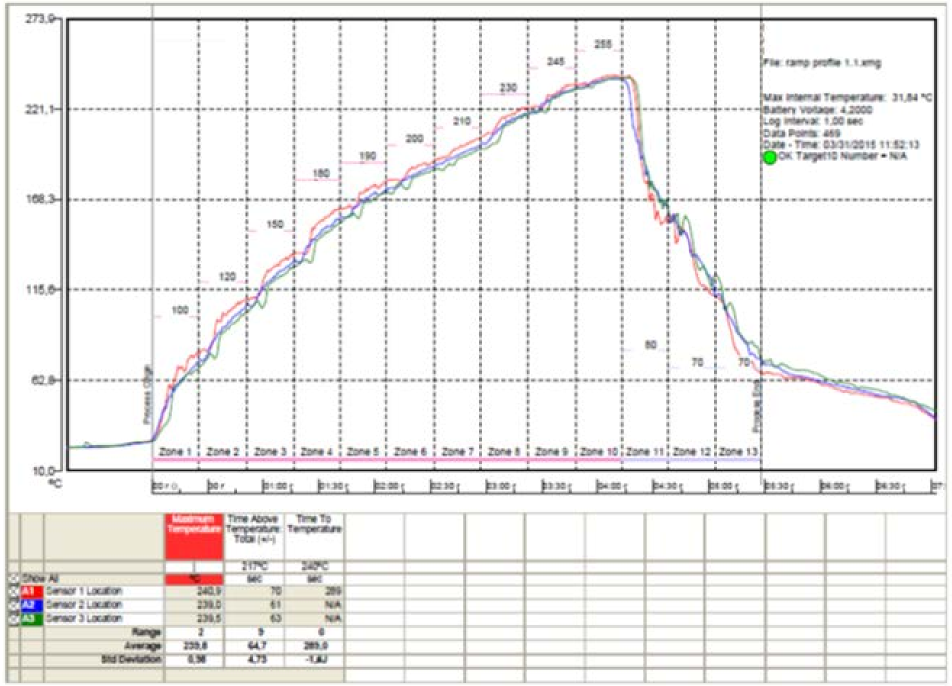
Results

Reflow Profile Variations			
	Max Temp (°C)	ΔT for Max Temp (°C)	TAL (sec)
Lead-free Solder Paste			
Recommended ramp reflow profile	239.8	-	64.7
Ramp reflow profile variation (-10°C peak)	228.6	-11.2	17
Ramp reflow profile variation (-15°C peak)	224.6	-15.2	13.3
Leaded Solder Paste			
Recommended ramp reflow profile	217.3	-	65.3
Ramp reflow profile variation (-10°C peak)	206.2	-11.1	25.7
Ramp reflow profile variation (-15°C peak)	202.4	-14.9	19

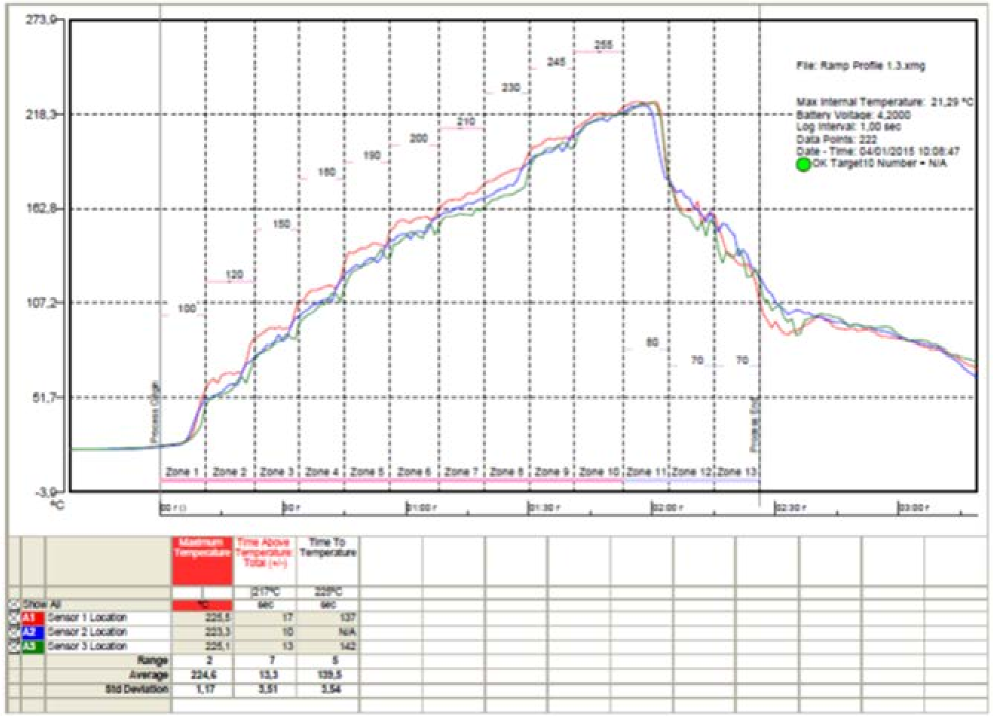
- TAL: Time Above Liquidus
- Liquidus temperature is 217^{o}C and 183^{o}C for the lead-free and leaded pastes respectively

Results

- Lead-free Ramp Profile



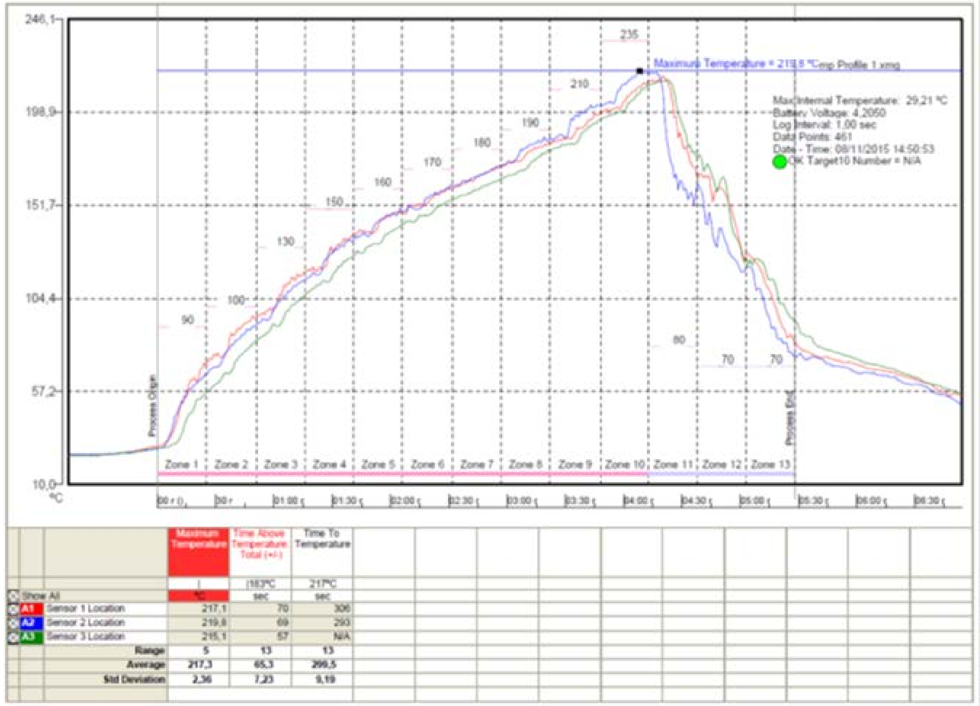
Recommended Reflow Profile



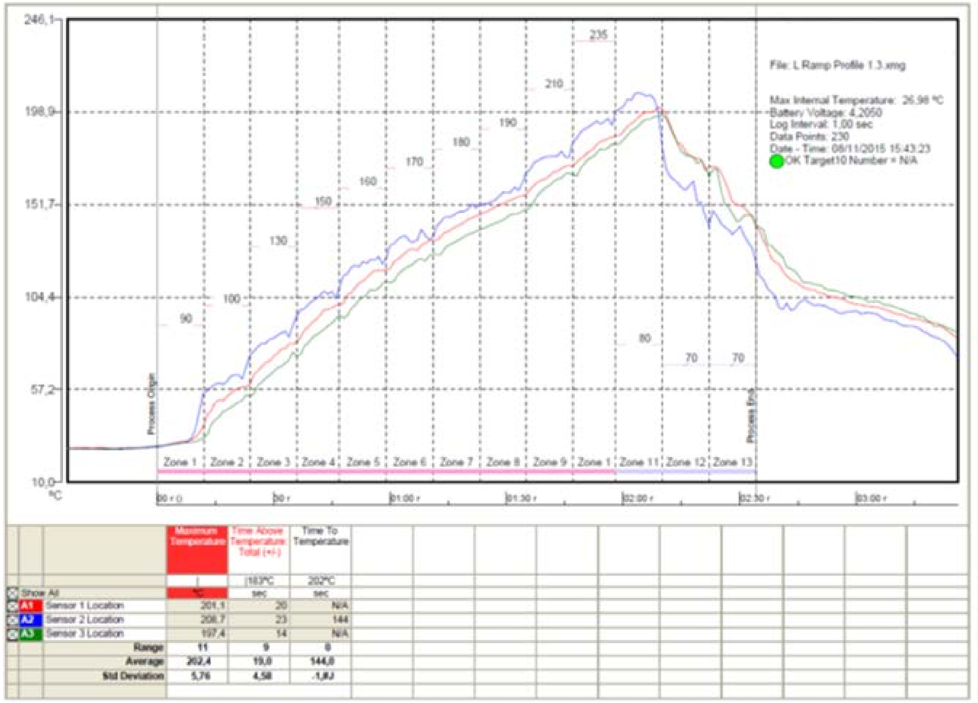
Reflow profile variation (-15^{O}C target)

Results

- Leaded Ramp Profile



Recommended Reflow Profile



Reflow profile variation (-15^{o}C target)

Results

- Simulated reflow profiles that averaged -11^{o}C and -15^{o}C below peak temperature
- Five (5) test vehicles were prepared for each paste type
  - Three (3) exposed to the manufacturers' recommended ramp profile and the -10^{o}C and -15^{o}C ramp profile variations, were not cleaned
  - Two (2) exposed to the -10^{o}C and -15^{o}C ramp profile variations, were cleaned
- Thirty (30) test vehicles were reflowed and subjected to SIR analysis

Results

- SIR Test Results

Solder Paste Type		Reflow Profile	Cleaned	SIR Test Result
Lead-free	Paste A	LF Ramp	No	Pass
		LF Ramp (-10°C)	No	Pass
		LF Ramp (-10°C)	Yes	Pass
		LF Ramp (-15°C)	No	Pass
		LF Ramp (-15°C)	Yes	Pass
	Paste B	LF Ramp	No	Pass
		LF Ramp (-10°C)	No	Fail
		LF Ramp (-10°C)	Yes	Pass
		LF Ramp (-15°C)	No	Fail
		LF Ramp (-15°C)	Yes	Pass
	Paste C	LF Ramp	No	Pass
		LF Ramp (-10°C)	No	Pass
		LF Ramp (-10°C)	Yes	Pass
		LF Ramp (-15°C)	No	Pass
		LF Ramp (-15°C)	Yes	Pass

Results

- Result: Lead-free Pastes
  - All pastes reflowed at the manufacturers' recommended profile had passing SIR results
  - Ramp reflow profile variation had no effect on the SIR results with Paste A and C
  - Ramp reflow variations at -10^{o}C and -15^{o}C with Paste B resulted in failed SIR results for the test vehicles that were not cleaned

Results

- SIR Test Results

Solder Paste Type		Reflow Profile	Cleaned	SIR Test Result
Leaded	Paste D	L Ramp	No	Pass
		L Ramp (-10°C)	No	Fail
		L Ramp (-10°C)	Yes	Pass
		L Ramp (-15°C)	No	Fail
		L Ramp (-15°C)	Yes	Pass
	Paste E	L Ramp	No	Pass
		L Ramp (-10°C)	No	Pass
		L Ramp (-10°C)	Yes	Pass
		L Ramp (-15°C)	No	Pass
		L Ramp (-15°C)	Yes	Pass
	Paste F	L Ramp	No	Pass
		L Ramp (-10°C)	No	Pass
		L Ramp (-10°C)	Yes	Pass
		L Ramp (-15°C)	No	Fail
		L Ramp (-15°C)	Yes	Pass

Results

- Result: Leaded Pastes
  - All pastes reflowed at the manufacturers' recommended profile had passing SIR results
  - Ramp reflow profile variation had no effect on the SIR results for Paste E
  - Ramp reflow variations at -10^{o}C and -15^{o}C with Paste D resulted in failed SIR results for the test vehicles that were not cleaned
  - Paste F only had failing SIR results for the -15^{o}C in which the test vehicle was not cleaned

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Conclusion

- Maximum board temperature and TAL are each critical to the formation of proper solder joint and inert resin layer
- Reflow optimization can be challenging given board density and component temperature sensitivity
  - Resulting in uneven PCB surface temperature
  - For No-Clean solder pastes, exposed flux activators may be present as a result

Conclusion (cont.)

- All solder pastes passed SIR when reflowed with the recommended profile
- Lead-free Pastes A, C and Leaded Paste E had passing SIR results when soldered with reflow profiles that were 10^{o}C and 15^{o}C below the recommended peak temperatures
- Lead-free Paste B and leaded Pastes D & F failed SIR tests when reflowed below the recommended peak temperature and not cleaned although each paste passed SIR if cleaned post reflow and prior to the SIR tests

Conclusion (cont.)

- Assemblies exposed to the manufacturers' recommended reflow profile resulted in passing SIR results
- Few solder pastes exposed to lower than recommended peak reflow temperatures resulted in SIR failure
- Effective post reflow assembly cleaning can ensure a passing SIR result and resulting product reliability

Thank you!
Questions?

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