Reflow Soldering of PCB Components with Mixed Thermal Mass

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Abstract

Growth of electrical vehicles and 5G technologies may impact the landscape of soldering equipment used for printed circuit board (PCB) assemblies. These applications require large multi-layer PCBs that contain small surface mounted devices (SMD) together with heavy transformers and capacitors. This mismatch of thermal mass creates challenges for reflow process and specifically for convection ovens. Large or heavy components usually require long total heating time which may cause small components to overheat. The paper includes comprehensive research to identify alternative technologies or viable modifications/additions to existing convection reflow process that can provide more uniform heating and meet high throughput requirements.

The study identifies the limits of traditional convection ovens. What mass components can't be soldered together with small packages like 01005 within the required process window using lead-free alloys. All considering solder pastes properties and limitations, maximum peak temperature and Time Above Liquidus (TAL) requirements as well as fan speed limitations (no component movement).

Statistical techniques such as "Box Behnken" have been performed to determine the limits of this soldering process. An investigation of available commercial solutions and emerging technologies that may help mitigate above technical challenge and enable future opportunities in convection reflow was part of the research. Experiments to improve the heat transfer in convection reflow included combination of reflow and conduction heating. The results of these process optimizations are presented.

Introduction

For the very small components the solder paste deposit is small. The printing process should have sufficient stencil release to make sure there is enough solder paste to guarantee proper wetting and solder fillet. Even though there might be enough paste there is a potential risk for graping. The small amount of paste may not contain enough activators to provide proper solder wetting. As a result, the solder joint may look like grapes and has reduced strength. The key parameter to avoid this is the flux activation. It is about oxidation of the solder paste spheres which can be avoided by having the right chemistry and provide an oxygen free solder environment. The larger high thermal mass devices required longer heating processes that is in contradiction with the flux activation system.

The second risk for very small devices is overheating. The higher the temperature settings of the oven the better for the high thermal mass devices. A zone temperature of 280°C will heat up the heavy components better, but it may overheat the small devices. Typical the components may not exceed 260°C. This limits the zone set point of the ovens to maximum 260-265°C.

The third risk for the small components is that the time above liquidus exceeds 90 seconds. The JEDEC/IPC-020 standard defines the maximum time above liquidus but for reliability the inter metallic layer is the critical part. In vacuum applications, this may become more critical because to avoid splattering of the flux it is important to wait a sufficient time (approximately 30 seconds) before starting to decrease the pressure in the chamber. This extra time results in a thicker inter metallic layer that is less strong and may result in early failure.

Define the Limits of Convection Reflow Ovens

The IPC-7530 standard describes the reflow profiling. A solder profile is not only product specific but is also flux and alloy dependent. In this paper the lead-free process using a SAC305 alloy is selected since this is the most common process in the industry at this moment. During the process there are some critical parameters that should be met:

- The peak temperature should be maintained between 230°C and 245°C.
- The dwell time above the liquidus 60-90 seconds.

The dwell time also called time above the liquidus (TAL) in reflow refers to time the temperature of the solder remains above the liquidus temperature (for SAC305 217°C), which is the temperature the solder melts and becomes liquidus. This parameter (TAL) is critical for the quality of the solder joint and its reliability. A sufficient TAL is required to ensure proper wetting and bonding of the solder joints but not excessively long to avoid potential issues like solder joint defects or component damage due to exposure to high temperatures.

The maximum peak packaging body temperatures for small components (<1.6 mm thickness) are defined in the JEDEC-020 specification to be not more than 260°C. For the components the TAL should be between 60 and 150 seconds. Summarizing the requirements:

- Small components not exceeding 260°C for 150 seconds.
- High thermal mass components not less than 60 seconds above 230°C.

To achieve these requirements a convection, reflow oven has multiple parameters to adjust. First the heating length and the number of heating zones have influence on the profiling. More zones make it easier to profile more accurately. The heat transfer depends on the design of the blower box, the type of the fan and the fan speed. A higher fan speed will increase the heat transfer but when the speed is too high components may move.

Impact of Fan Speed

The zones are set at different temperatures. The efficiency of these settings is dependent on the heat transfer. The fan speed is critical in transferring the heat of the hot gas into the assembly and the fan speed is defined by the frequency inverter. A higher frequency results in better heat transfer, but there are limitations. The graph shows the relationship between the frequency setting and the flow rate of the hot gas in the zone.

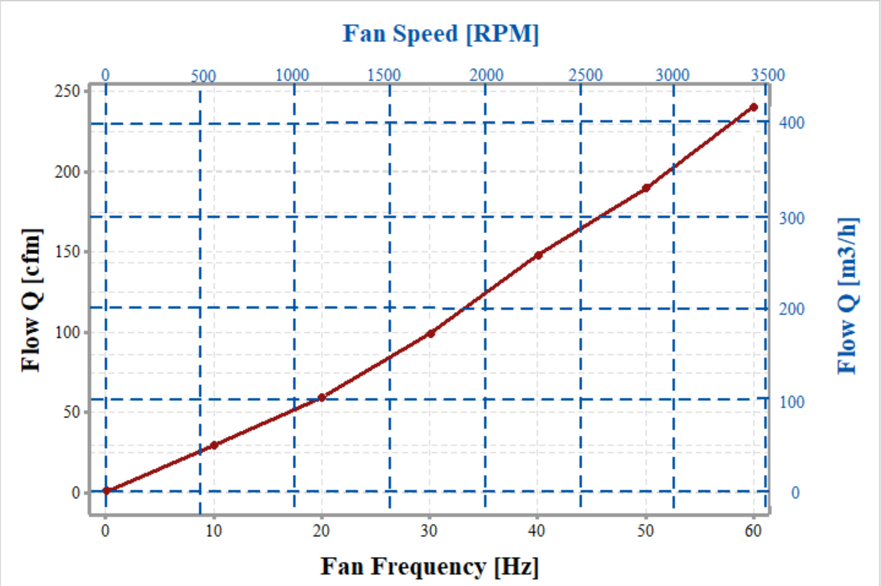

Figure 1. The Frequency [Hz] of the Fan Versus the Flow Rate of the Gas at 20°C.

Increasing the fan speed increases the heat transfer coefficient of the oven. A too high gas flow may shift the components. The gas flow can be measured with an Aero M.O.L.E.®. This device can measure the flow of the gas at ambient temperature.

Figure 2. Three Probes Measuring the Horizontal Gas Flow During Transportation Through the Reflow Oven.

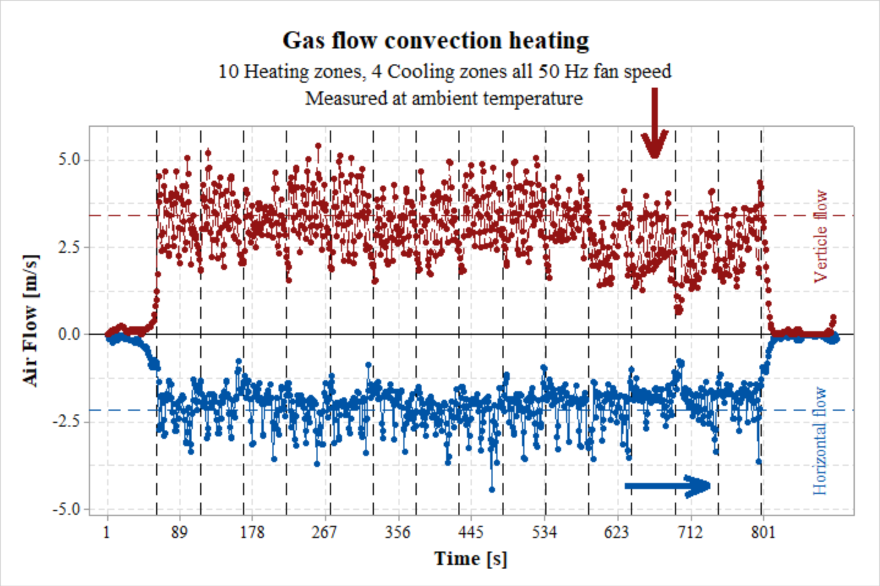

Figure 3. Gas Flow in the Reflow Oven at Ambient Temperature.

The flow rate was measured for different fan speeds. To get the best heat transfer a turbulent flow is better. As the graph shows, the flow rate changes continuously during the reflow process.

Table 1. Flow Rates at Different Fan Speeds.

		20 Hz	40 Hz	50 Hz	60 Hz
Vertical flow [m/s]	Average	1.04	2.42	3.39	4.47
	Maximum	1.81	4.16	5.39	9.02
	Minimum	0.56	1.57	2.32	2.99
Horizontal flow [m/s]	Average	0.71	1.60	2.18	2.72
	Maximum	1.79	3.04	4.46	4.49
	Minimum	0.46	1.05	1.61	1.65

The table shows the flow rates at different frequencies of the fan at ambient temperature because the sensors can't withstand the high reflow temperatures. To understand what fan speed is acceptable another test was done. The blowing test board is used to define the maximum convection rate during reflow profiling. The maximum blowing speed should be determined. For this test 9 electrolytic capacitors (diameter 10 mm, height 8 mm and weight 0.825 g) are placed on a test board that is run through the reflow oven. The elco's shall be inside of the 40 mm circle after running through the reflow oven at the required heating profile. The test is repeated for different frequencies of the fan. The next picture shows that even with 60 Hz the component misalignment is minimal. There is no significant displacement of components, and all are well within the 40 mm circle after the heating cycle.

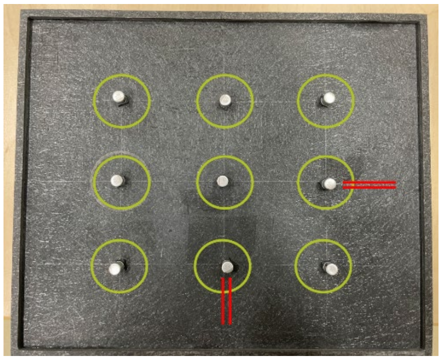

Figure 4. No Component Misalignment at 60 Hz Fan Speed.

Calculate Heat Transfer Coefficient of the Oven

To characterize the specific physical properties of a convection, reflow oven a test vehicle is used. The difference in temperature as measured between the air and the high mass sensors demonstrates the efficiency of the oven to transfer heat, or heat transfer value. A higher heat transfer value allows for tighter control over the reflow process. This tool contains 3 accurate thermocouples to examine temperature differences in the oven (accuracy 1.1°C or 0.4%). These temperatures are compared to the temperatures of the high thermal mass sensors. These are made from 6061 Aluminum rod and weigh 17.713 g. The density of this material is 2.710 kg/m^3.

To calculate the heat transfer in a convection oven the formula used is:

$$Q = \alpha * A * \Delta T \text{ (W/m}^2\text{K)}$$

Q = heat transfer rate (W/m^{2}K)
α = heat transfer coefficient (W/m^2/K)
A = surface area (m^2)

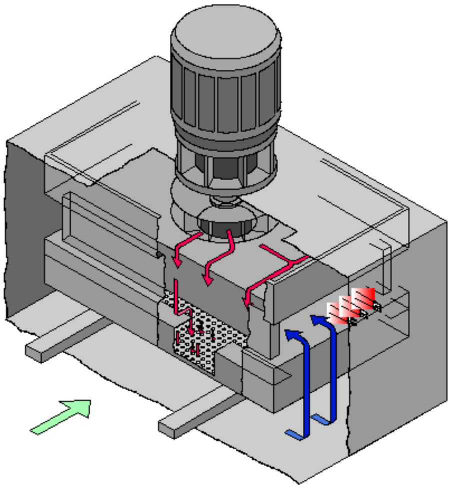

Figure 5. Cross Section of a Convection Heating Zone.

A Design of Experiment was run to determine the impact of the fan speed and the zone temperatures on the heat transfer. The outcome of the experiment is that the fan speed has a significant impact on the heat transfer. Thus, the final temperature of the assembly after reflowing is not only defined by the conveyor speed and zone temperature settings but also by the speed of the fans. This parameter can be used to bring more heat in high thermal mass assemblies.

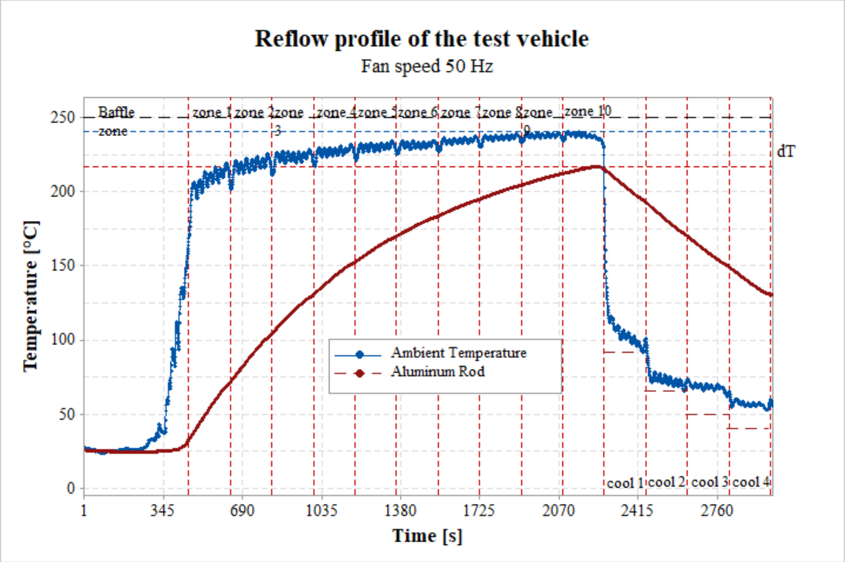

Figure 6. The Reflow Profile for Fan Speed 50 Hz and All Zones at 250°C.

The graph shows the peak temperature of 217°C for the Aluminum rod. The closer the temperature of this rod is to the set-point of the zones the better the heat transfer and the smaller the dT (temperature difference between the two sensors). For this run the calculated heat transfer is 140 W/m²K (or 24.7 BTU/ft²hr²). For a dT = 0°C the heat transfer should be 260 W/m²K or higher. With all zones at 250°C set-point and frequency at the maximum of 60 Hz the heat transfer was 152 W/m²K by far not enough to achieve the target of dT = 0°C. The limits of the convection reflow have been reached. Higher temperature settings will damage small components and a higher fan speed will move the small components.

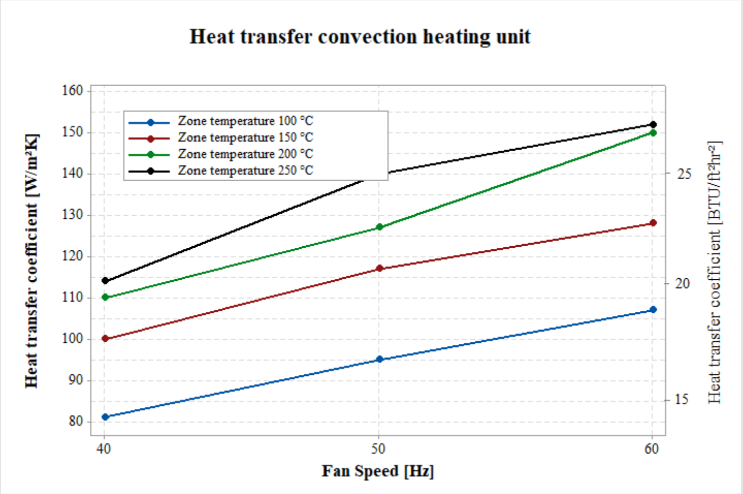

Figure 7. Calculated Heat Transfer Coefficients for Different Zone Temperatures and Fan Speed.

Conveyor Speed and Time Above Liquidus

A longer oven opens results in a higher throughput. The conveyor speed influences the time above liquidus. An oven with 12 heating zones can be divided into 4 preheat, 4 soak, and 4 peak zones. Four zones are equal to 1.42 m peak zone length. A Box Behnken experiment was set up to define the impact of the conveyor speed and define the maximum boundaries of the reflow oven. If the set temperature of the zones is not higher than 260°C the small components cannot be overheated. With four peak zones at 260°C the maximum temperatures can be achieved.

Table 2: Parameters Box Behnken Experiment

Conveyor speed	Fan speed	Alu Rod mass
[cm/min]	[Hz]	[g]
50	40	0
100	50	8.6
150	60	17.2

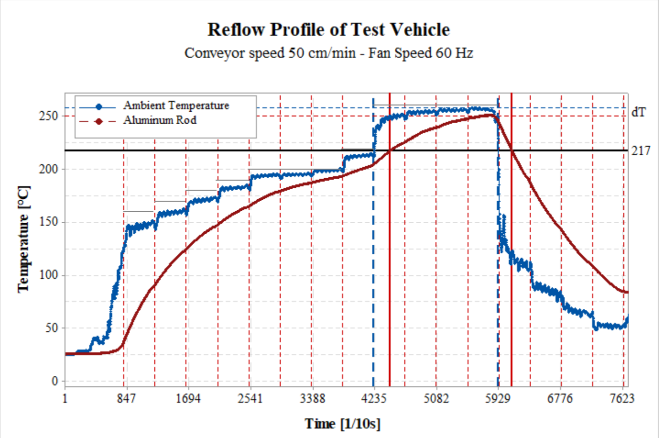

Figure 8. The Maximum Reflow Oven Settings: Peak Zones at 260 °C, Fan Speed at 60 Hz, and Conveyor Speed 50 cm/min.

With the maximum settings as shown in the graph the half Aluminum rod (8.6 g) peak temperature is close to the ambient temperature (simulating the smallest component). The dT is only 8°C. However, the time above liquidus is 170 seconds, significantly longer than the 150 seconds.

Alternative Heating Method: Vapor Phase

The heat transfer needs to be significantly better to meet the requirements for soldering a very small and high thermal mass device together in one assembly. A well-known method is using vapor instead of heating with a gas. Vapor phase soldering exposes the electronic assembly to hot vapor, generated by a special liquid Galden that has a boiling point of 240°C. Once the assembly is transported into the boiling area the Galden condenses on the assembly. There is a minimal risk for thermal damage of the small components since the temperature will not exceed 240°C. To show the efficiency of this process the Aluminum rods were heated in a tabletop vapor phase unit.

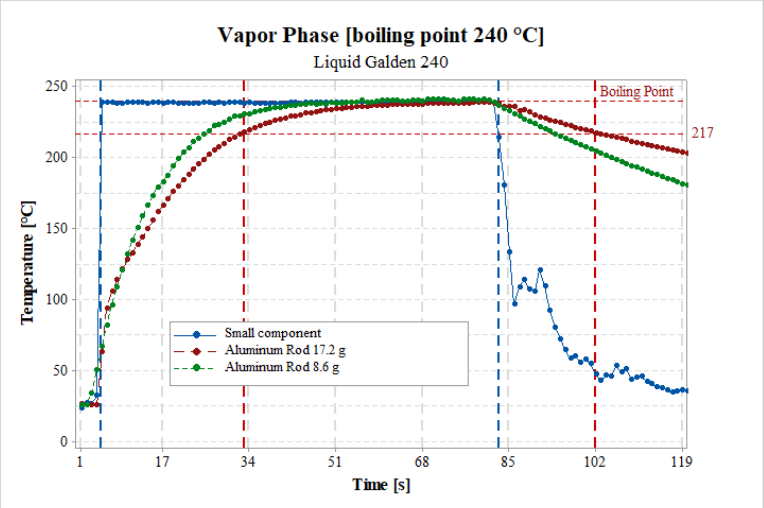

Figure 9. The Vapor Phase Heating Profile.

The profile shows the benefits of the vapor phase process. The dT is less than 1°C and the time above liquidus is 83 seconds for the thermal mass devices and 81 seconds for the small component. Technical vapor phase is better, but the process is a batch process and the gradient for the very small component is steep (some components are limited to 3°C/s).

Alternative Heating Method: Radiation

Another alternative is radiation heating. With Infra-Red light the Aluminum sample can be heated very fast. The advantage of radiation heaters is known from the wave solder machines where IR lamps are used to preheat printed circuit board assemblies.

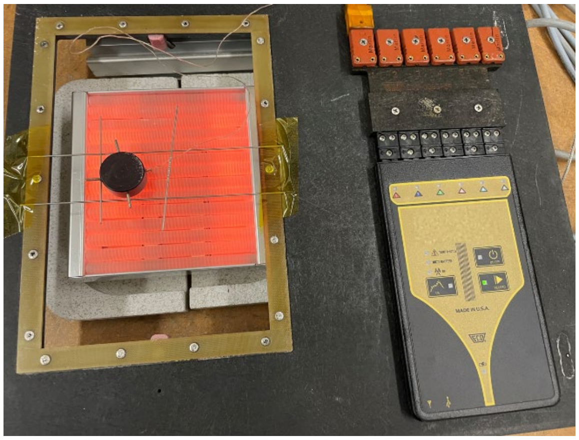

Figure 10. IR lamps (700W) Are Heating the Aluminum Rod.

The lamps emit infrared radiation which efficiently heats the Aluminum rod. The lamps enable rapid and controlled heating, but the wavelength is a critical factor that should be well considered for its application. The lamps selected in this application were efficient in heating up the Aluminum rod, but due to the wavelength and high radiation the FR4 material of the assembly started to delaminate.

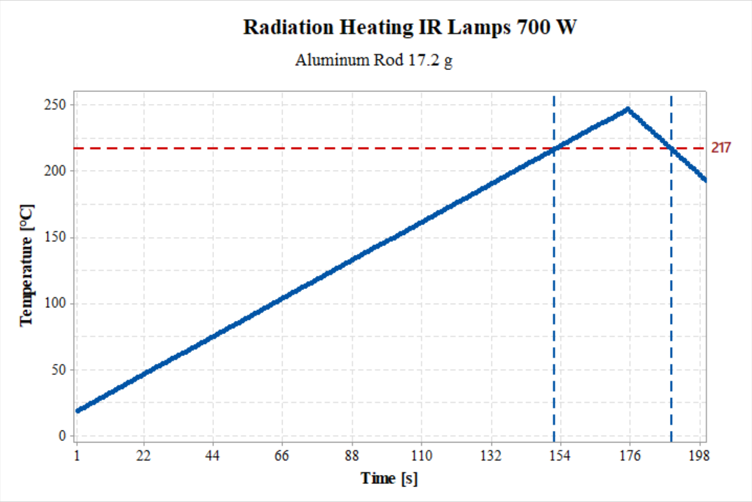

Figure 11. Heating Profile IR Heaters at 700W.

Infrared lamps were used in reflow applications but due to the large dT this method is not an option for soldering surface mount devices.

Convection Reflow with Additive Heaters

Convection reflows very heavy thermal mass devices without overheating small components can only be done when the heavy parts are heated with a separate heater. This added heater should only heat the heavy part without influencing the heating profile for the rest of the assembly. A possible solution would be placing the assembly in a pallet. The pallet should have an integrated heater with power supply.

A typical example of a high thermal mass component is a current sense resistor. The dimensions of this Cu metal device are 85x36x3 mm and the weight is 75 grams. In the experiments a similar Cu metal device 42x20x2.5 mm 17.2 grams is used. To heat a small device and this 17.2-gram Cu plate a linear is used. The profile is a 3-minute heating cycle. The first zone is set at 100°C and the last peak zone has a temperature of 280 °C.

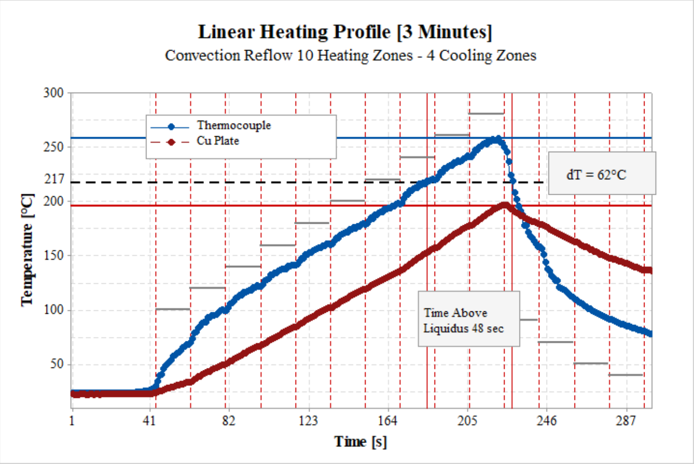

Figure 12. Linear Heating Profile for Small Component and Cu Metal Part.

The figure shows the difference between the Cu 42x20x2.5 mm plate and the small component. The dT is 62 °C and the Cu plate is not even reaching the melting temperature. Since it is not possible to measure the temperature of the smaller parts the temperature of the thermocouple is the reference.

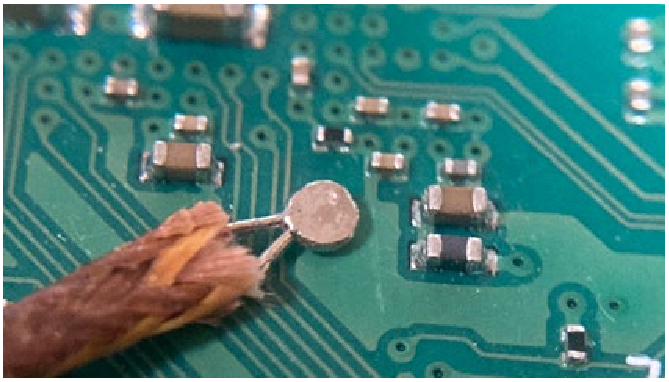

Figure 13. Small SMD Components Together with a Thermocouple.

Thermocouple wire is already 0.127 mm compared to 0.4x0.2 mm size of the 01005 component. To reduce the dT different heating elements were mounted on the Cu plate and tested. Most successful were the polyimide heating foils that were glued on the Cu plate like the figure below.

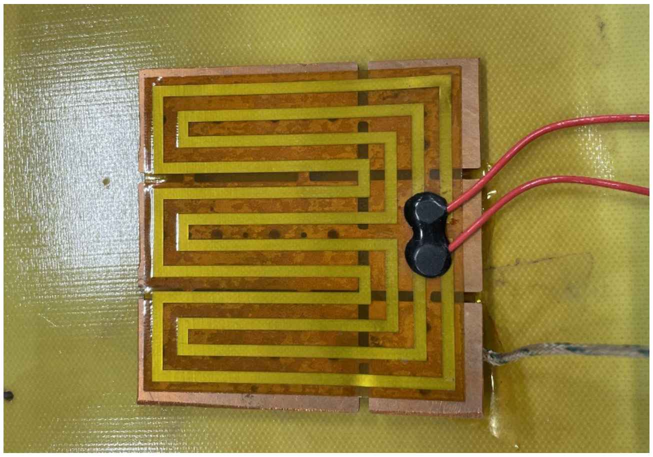

Figure 14. Polyimide Heating Foil Glued on the Cu Plate.

The picture shows a 60x60 mm heating foil. For the 42x20x2.5 mm Cu plate a smaller heating foil 45x13 mm 24V – 22W was mounted on the plate. Several runs showed that with 17 V the temperatures of the small component and the Cu plate were very close. The heating element was connected to a power supply by long wires going through the oven. The wires were disconnected the moment the assembly entered the cooling zone. In the cooling zone the heaters were off.

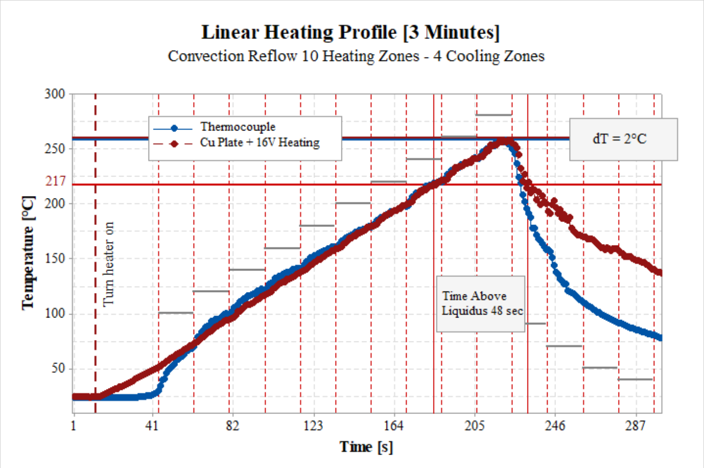

Figure 15. The Same Heating Profile as in the Previous Figure but now with Polyimide Heater at 17 V.

The heater was switched on 30 seconds before the board entered the oven. The peak temperature of the Cu plate increased from 196°C to 257°C. Both small component and Cu plate are 48 seconds above the liquidus and the dT decreased from 62°C to only 2°C.

Potential Heaters

The polyimide flex heaters are effective in heating the Cu or other heavy components. The downside of this heater is that it is glued to the component for the best heat transfer. So, it can be used only once. Another heating element is made from silicone. A round silicone (diameter 35 mm) heater was placed on the Aluminum rod and heated. This heater was 12V and 10W.

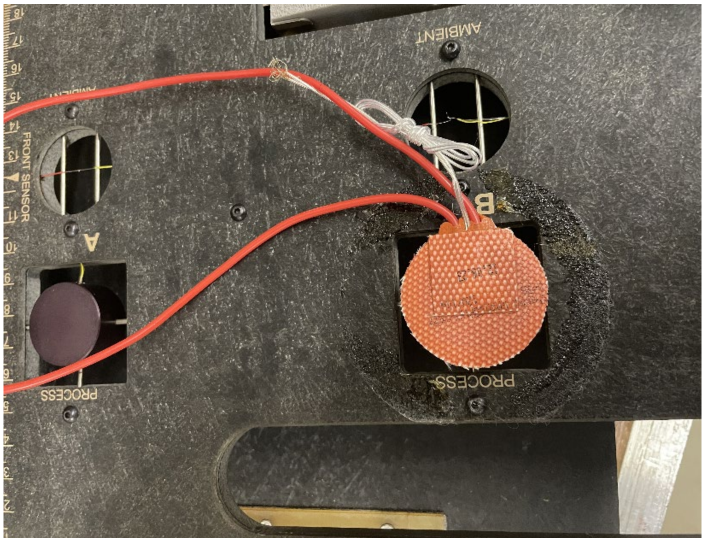

Figure 16. The Silicone Heater on top of the Aluminum Rod.

Two minutes before the unit was reflowed the Silicone heater was switched on. As a result, the Aluminum rod was approximately 70 °C before it entered the first heating zone. The Silicone heater was blocking the convection heat of the oven to heat up the Aluminum rod. Instead of achieving a temperature close to the thermocouple temperature its peak temperature was only 4 °C higher. The Silicone heater was not strong enough to heat the Aluminum rod.

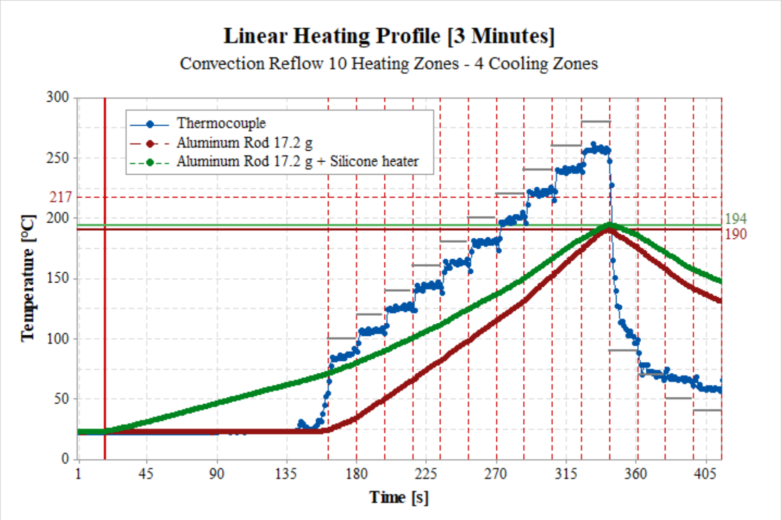

Figure 17. The Green Line Shows the Aluminum Rod with Silicone Heater.

A perfect heater for this application would be a Peltier element. This element is a thermoelectric cooler that creates a temperature difference between its two sides. The Peltier element can be used for both heating and cooling. When mounted in a pallet it can heat the Cu plate. Once the pallet enters the cooling zones the current can be switched and the element cools the Cu plate. The advantage of this element is that it can be used multiple times. Unfortunately, these Peltier elements can't withstand high temperatures. They are available with a maximum operation temperature of 200 °C, where this limit is defined by the reflow temperature of solder and sealing. Tests with these elements failed because of the reflow temperatures.

Discussion

Additional heaters to heat the high thermal mass components can solve the problem of the large dT between small components and high thermal mass devices. In the test here its feasibility is proved. In the next steps the heating element should be integrated in the pallet as well as a power device for it. Each board will have its own pallet and heating elements. This comes with additional costs. More research is required to make this concept successful. Heating methods and required power are points to improve. The heating elements should not interfere with the cooling.

Technically there are more possible solutions to solve the problem with soldering high thermal mass devices and very small components:

1. Split into two reflow cycles: First solder high thermal mass component with high temperature solder or SAC305. Second reflow small SMD components.
2. Split the reflow process in two cycles: First small SMD's with SAC305. Second reflow cycle the large devices using a low temperature solder.
3. Split into two reflow cycles: First solder small SMD's. Second reflow high thermal mass component with SAC305 and cover SMD's with insulation (no reflow).

Conclusions

In this paper the limitations of the reflow process have been discussed and boundaries are defined. To meet the mismatch between high thermal mass devices and small fine pitch components the use of additional heaters for the large thermal devices is an option. The profiles show that the additional heaters can decrease the dT to acceptable levels. Next steps to make this system work in an industrial environment are to define requirements for heaters, integration in pallet materials and design a method to power the heaters.

Acknowledgements

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References

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