The Development of a Qualification Temperature Profile for Lead-free Reflow Soldering

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Abstract
A reflow soldering profile has been developed for SnAgCu solder paste regarding mass production requirements, measurement and furnace tolerances as well as reliability requirements of automotive industry. The profile is a limiting line between the qualification of the semiconductor device and the assembly process to avoid harmful stressing of the components. Measurements were performed on a test printed circuit board which was especially designed for such investigations. Regarding non-hermetic solid state surface mount devices three temperature classes have been identified with peak temperatures of 245 °C, 250 °C and 260 °C. In addition to the peak temperature, the necessary time of the temperature plateau 5K below the peak has been defined based on the measurements.

Introduction
To achieve a reliable solder joint the conventional reflow soldering process with SnPb solder paste is often performed at minimum peak temperatures of about 203 °C, i. e. at least 20 K above the liquid temperature of SnPb (T_{liquid}=183 °C). The lead-free soldering process with SnAgCu solder paste (T_{liquid}=217 °C) has to be performed at a minimum peak temperature of T_{min} = 230 °C – just 13 K above the melting temperature – to minimize the heat impact on semiconductor and passive components and on the printed circuit board. Despite the relatively low temperature, the reliability of the solder joint has to be assured, for instance for safety relevant applications in automotive industry. To reach this target, the preheating time before solder peak temperature and the time at T_{min} have to be elongated for the lead-free process, i. e. minimum 20 s at 230 °C.
In the following, the development of a temperature profile for SnAgCu reflow soldering will be presented which considers the different aspects of serial production, reliability of solder joints and heat impact on the devices.

Prerequisites
On the basis of automotive electronic control units (ECU) with a moderate range of package sizes and variety, a reflow profile has been developed for SnAgCu solder paste with a melting point at about T_{liquid}=217 °C (1) . The SnAgCu solder paste is the worldwide accepted material for lead-free reflow and wave soldering in mass production (2). The experiments have been performed under mass production conditions (850 mm/s = 33 inch/min) using the leading edge technology oven equipment, status 2003, i. e. multiple heating zones, full convection, N_2 atmosphere.
As described above the minimum peak temperature of 230 °C has to be reached for at least 20 s, which corresponds to 1s at 233 °C resulting from the peak shape (see Figure 1).

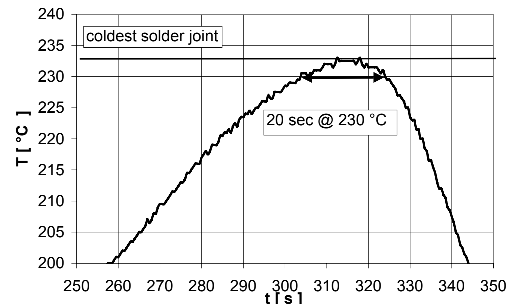

Figure 1 - Curve shape for a peak temperature of at least 20 s at 230 °C. The maximum temperature of 233 °C is reached for 1 s

Test board
For the experiment a special test printed circuit board (PCB) was designed. Polyimide resin with a glass transition temperature of T_g=260 °C was used as base material for the PCB. The test board represents a projection of the whole automotive ECU spectrum on one PCB. The largest temperature difference (ΔT) between the coldest solder joint and the hottest point existing on this printed circuit assembly (PCA) spectrum is reflected on this test board (ΔT can be even larger for other PCAs). Apparently, the hottest

point on the PCA is the PCB itself. The coldest solder joint – defined by the largest thermal mass – has to reach the 230 °C for 20 s and is defined by thermographic measurements on serial boards and based on profound soldering experience.

Tolerances

Regarding the tolerances during temperature profiling, different systematic failures have to be considered. First of all, there is the failure during temperature measurement itself. The measurement is performed on top in the center of the packages with a well defined and repeatable preparation technique. Nevertheless, the failure due to preparation has to be fixed with ±0.5 K. In addition, the thermocouple (NiCrNi) together with the evaluation unit has an accuracy of ±1 K for pre-selected thermocouples (the standard tolerance given by the manufacturer without selection is ±1 K just for the thermocouple itself). Altogether, the systematic failure due to temperature measurement is:

- temperature measurement: ± 1.5 K.

The tolerances for the furnace are given by the oven suppliers as following:

- furnace loading (min./max.): ± 0.5 K
- long term stability (5s-tolerance): ± 2.5 K.

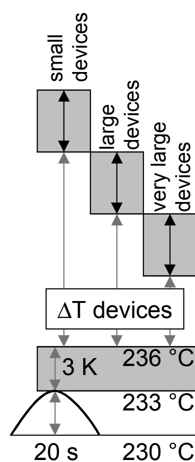

Figure 2 – Schematics showing lower and upper tolerances of the temperature window for the SnAgCu reflow solder profile. The temperature window is defined by the temperature splitting ΔT of the devices. The lower tolerance of 3 K results out from the Gaussian error propagation for furnace loading and long term stability as well as temperature measurement. In the upper tolerance of 5 K – 6.5 K (not indicated in the figure), the longitudinal and transverse temperature tolerances are included

The lower tolerance of the temperature window is composed out of furnace loading, long term stability and temperature measurement. Because these failures are independent, the Gaussian error propagation can be applied which results in a total lower tolerance of 3.0 K. As a consequence, the coldest solder joint has to be profiled at 236 °C, i. e. 3 K higher than without any error.

Dependent on the test board design a longitudinal and a transverse temperature profile have to be considered. During the experiments it was found that the temperature at the front and back end of the test PCA is always lower than in the middle, presumably due to the flowing conditions around the PCA. Due to the reflow furnace specification the transversal temperature profile is always present.

The thermal mass on the test board which represents the coldest solder joint on the serial boards already includes both tolerances.

For the upper tolerance of the temperature window the transversal and longitudinal temperature tolerances (2 K – 3.5 K) have to be added resulting in a total upper tolerance of 5 K – 6.5 K.

Regarding the whole temperature window, in addition to the measured ΔT of the devices a total temperature tolerance of 8 K – 9.5 K has to be considered (see Figure 2).

Peak form and width

In order to obtain 230 °C for 20 s at the coldest solder joint and a peak temperature $T_{peak} \leq 260$ °C for the PCB and the smallest devices, e. g. SOT23, LQFP (14 x 14), LQFP (20 x 20), a hat type profile is necessary, as can be seen in Figure 3. This yields in 40 s at $T_{max} - 5$ K = 255 °C at the hottest devices and the PCB.

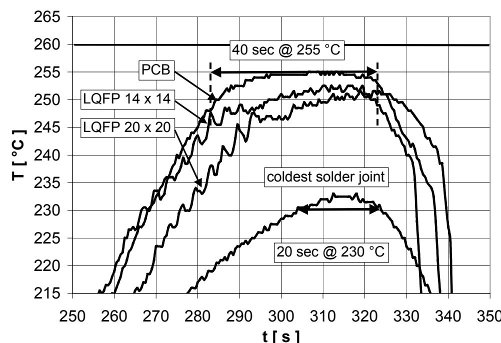

Figure 3 – A hat type profile with 40 s at T_{max} - 5K = 255°C for the small devices and the PCB results from the requirement of 230 °C for 20 s at the coldest solder joint

Device classification

To classify the non-hermetic solid state surface mount devices into temperature groups regarding the reflow peak, the heat capacity and heat conductivity must be evaluated. For simplification, the advantage of the component similarity with respect to the composition

(molded silicon) is taken into account and just the package volume and thickness are considered.

In Figure 4, the measurements performed with the testboard described above are shown. The transportation speed was 850 mm/s (33 inch/min) and the temperature measurements were performed in the center on top of the packages. In total, the temperature profiles for 19 different package types were measured on a multiple heating zone reflow oven with full convection, under N_2 atmosphere. For the better overview just three representative measurements are depicted. Between the coldest solder joint and the PCB itself, i. e. the hottest point, a temperature difference of 13 K was measured.

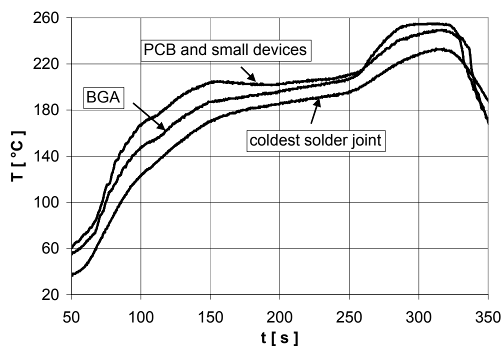

Figure 4 – Representative test board measurements performed in the center on top of the packages. The transportation speed was 850 mm/s (33 inch/min) in a full convection multiple heating zone reflow furnace under N_2 atmosphere

In addition to the measured peak temperatures, the tolerances have to be considered. In Table 1, the measured and corrected peak temperatures are listed. Here the tolerances of the temperature measurement, furnace loading and long term stability, transverse and longitudinal temperature profile are considered resulting in temperature differences between the actual measured and the corrected values of up to 9.5 K for the QFP144 (28 x 28).

Obviously, the classification into three temperature classes results from the corrected values, i. e. 245 °C, 250 °C and 255 °C. Regarding these three classes the measured ΔT between the coldest solder joint and the different packages are 4 K, 9 K and 14 K, respectively, whereas the corrected ΔT are 10 K, 15.5 K and 19 K.

Referring to volume and thickness of the devices, the three classes can be split into nine subclasses depicted in Table 2.

Based on the fact that a lot of the small components are commonly qualified with a 260 °C peak temperature reflow profile, the highest temperature class can be raised to 260 °C, whereas the other device classes stay at their temperatures. The benefit of qualifying the small components at 260 °C is the possibility to use older reflow furnaces for less complex boards.

Table 1 - Measured and corrected peak temperatures for 19 different non-hermetic solid state surface mount devices. In the corrected values the tolerances of the temperature measurement, furnace loading and long term stability, transverse and longitudinal temperature profile are included. Three temperature classes can be identified with measured ΔT to the coldest solder joint of 4 K, 9 K and 14 K resulting in corrected values of 10 K, 15.5 K and 19 K

package (measurement on top of package)	measure-ment	final values with tolerances
	[°C]	[°C]
coldest solder joint	233.0	**236.0**
PLCC 84 (30 x30)	232.5	**241.0**
QFP160 (28 x 28)	233.5	**242.0**
PLCC 68 (24 x 24)	233.5	**242.5**
PLCC 44 (17 x 17)	234.0	**242.5**
PLCC 52 (19 x 19)	234.0	**243.0**
DO218	236.0	**244.5**
MO-166	237.0	**246.0**
QFP-exp. pad (20 x 14)	237.5	**246.0**
SO28	237.5	**246.0**
PLCC 28 (12 x 12)	238.0	**246.0**
QFP144 (28 x 28)	237.0	**246.5**
MO-188 (14 x 14)	237.5	**247.0**
QFP80 (20x14)	238.5	**247.0**
TO 263	239.5	**247.5**
SO 44 XL	240.0	**248.0**
QFP 80 (14 x 14)	240.5	**248.5**
BGA (24 x 24)	240.5	**249.5**
LQFP-MS026 (20x20)	242.0	**251.5**
LQFP 100 (14 x 14)	243.5	**252.5**
temperature on PCB	247.0	**255.0**

To clarify this argumentation, the variation of ΔT between leading edge of technology (status 2003: full convection, multiple zone reflow furnaces) and state of the art reflow equipment for variously complex boards is graphically presented in Figure 5. For a complex board soldered on a leading edge reflow furnace with multiple zones the peak temperatures of the device classes are as described in Table 1. For less complex ECUs using the same reflow furnace the maximum temperatures for the device classes are lower (see Figure 5, step 1). But soldering the same less complex ECU on state of the art equipment, which is normally found in the production lines at the

moment, the temperature splitting between the devices rises. Fixing the temperature of the 250 °C class, the temperature of the small devices rises up to 260 °C (see Figure 5, step 2).

Table 2 – Correlation between the three temperature classes defined above and volume and thickness of the devices

thickness\volume	< 350 mm³	350 - 2000 mm³	> 2000 mm³
< 1,6 mm	260 (- 0) °C	260 (- 0) °C	260 (- 0) °C
1,6 - 2,5 mm	260 (- 0) °C	250 (- 0) °C	250 (- 0) °C
> 2,5 mm	250 (- 0) °C	250 (- 0) °C	245 (- 0) °C

Lead-free reflow temperature profile for classification of moisture sensitivity level

All the measurements and data result in the qualification reflow profile shown in Figure 6. For qualification and determination of the moisture sensitivity level (MSL), the devices have to be soldered at least three times above this temperature profile to ensure the reliability of the device during serial production. The soldering in mass production has to be done below this limiting temperature line with smaller temperature gradients to be sure that there is no harmful stress to the devices during the assembly process. Therefore this reflow profile is the limiting line between the device suppliers and the assemblers.

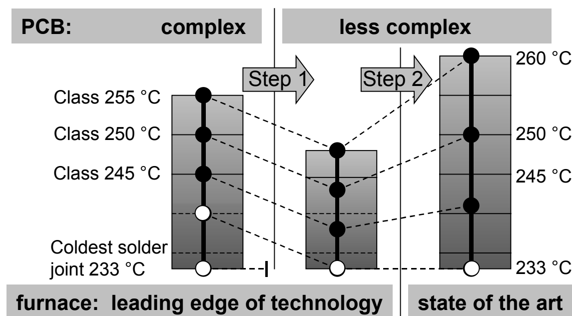

Figure 5 - Temperature splitting of devices on ECUs with varying complexity soldered on leading edge reflow equipment (status 2003, multiple heating zones, full convection, N_2 atmosphere) in comparison with state of the art equipment in production

In Table 3, the reflow profile is given in numbers again. The minimum times at $T_{max} - 5$ K result from the same measurements as shown in Figure 3 for the smallest devices.

Conclusion

Based on measurements performed on leading edge technology furnaces a qualification reflow profile for lead-free soldering with SnAgCu was developed as limiting profile between device qualification and assembly process assuring the high quality and reliability requirements of automotive electronics. The investigations lead to a separation of the non-hermetic solid state surface mount devices into three temperature classes regarding the temperature peak height and width sorted by volume and thickness. Different tolerances resulting out of temperature measurement, serial production conditions and board design have been taken into account and lead to tolerances up to 9.5 K. The tolerances can be reduced if the furnace tolerances could be minimized. This has to be addressed to the oven manufacturers in future.
Similar measurements will be performed for passive, non-molded devices during the next months with the target to get a similar temperature splitting for the different housings.

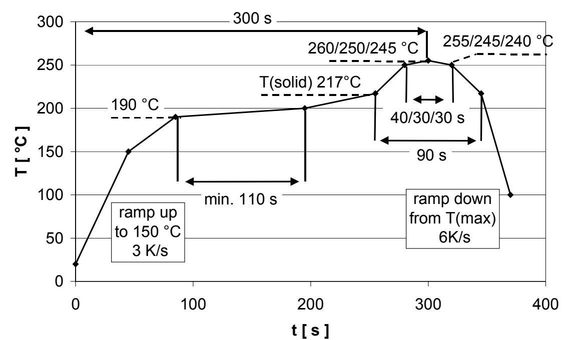

Figure 6 – Lead-free reflow temperature profile for MSL classification. Qualification has to be performed above the limiting temperature line, whereas the assembly process has to be performed with temperatures and temperature gradients below this line to avoid crucial stress to the devices.

Table 3 – Lead-free reflow temperature profile in numbers for the three device classes

Profile Features	Small Devices	Large	Very Large
preheat			
ramp-up rate to 150 °C	min. 3 K/s (average value over 10 s)		
time from 190°C to 200°C	min. 110 s		
peak			
ramp-up rate from 200°C to T_{peak}	0,5 K/s - 3 K/s (average value over 10 s)		
time above $T_{solidus}$ (min. 217 °C)	min. 90 s		
peak temperature T_{peak}	260 (- 0) °C	250 (- 0) °C	245 (- 0) °C
time above T_{peak} - 5 K	min. 40 s	min. 30 s	min. 30 s
cooling			
ramp-down rate from $T_{solidus}$ (min. 217 °C)	min. 6 K/s (average value over 10 s)		
general			
time 25 °C to T_{peak}	min. 300 s		

References

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(2) "Second European Lead-Free Soldering Technology Roadmap", Kay Nimmo, soldertec, Feb. 2003