# Reflow Defects with Lead-Free Soldering Moisture Sensitive Components

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**Abstract**
Soldering with lead-free solders has become an international standard. A study conducted by the Dresden Technical University and rehm Anlagenbau examines which influences various parameters have on soldering results. The study substantiated that, amongst other factors, the soldering atmosphere (nitrogen or air) and oven parameters have a significant influence on tombstoning. Excessively high soldering speeds cause more tombstones than lower speeds. Wetting results for the examined surface finishes (nickel-gold and immersion tin) depend upon the composition of the solder paste. Nitrogen in the soldering atmosphere significantly improves solder spreading.

The study also included ultrasonic examinations of various IC packages after reflow soldering. The tendency of the different packages to delaminate after convection soldering was compared with vapor phase and vacuum soldering.

## 1. The influence of various soldering and material conditions on the quality of finished SMD components.

The production of electronic components is influenced by many parameters. It is the objective of every optimized manufacturing process to keep quality parameters within the defined limits. Two large groups of parameters influence reflow quality: controlled and non-controlled parameters.

With the help of the design of experiments, it can be substantiated whether or not intentionally changing one or more factors results in a significant change to one or more response variables.

**Table 1 - Investigated factors**

| Factor | | Number | Type |
|---|---|---|---|
| A | Solder paste | 3 | Type 1, type 2, type 3 |
| B | Soldering atmosphere | 2 | Air $O_2$, Nitrogen $N_2$ |
| C | Surface finish | 2 | Immersion tin, nickel-gold |
| D | Temperature profile | 4 | Conveyor speed / peak temp. [cm per min. / °C]<br>55 / 247, 85 / 244, 125 / 244, 140 / 221 |

The lead-free solder pastes were selected in the basis of alloy and flux activity:

**Table 2 - Used types of solder paste**

| Solder Paste | Alloy | Flux |
|---|---|---|
| Type 1 | Sn96.5 Ag3 Cu0.5 | ORH0 |
| Type 2 | Sn95.5 Ag3.8 Cu0.7 | L0 |
| Type 3 | Sn95.75 Ag3.5 Cu0.75 | ROL0 |

The temperature profiles vary primarily with reference to preheating times and peak temperatures (see **figure 1**). Emphasis was placed upon generating limit temperature profiles by means of which barely acceptable soldering joints were obtained.

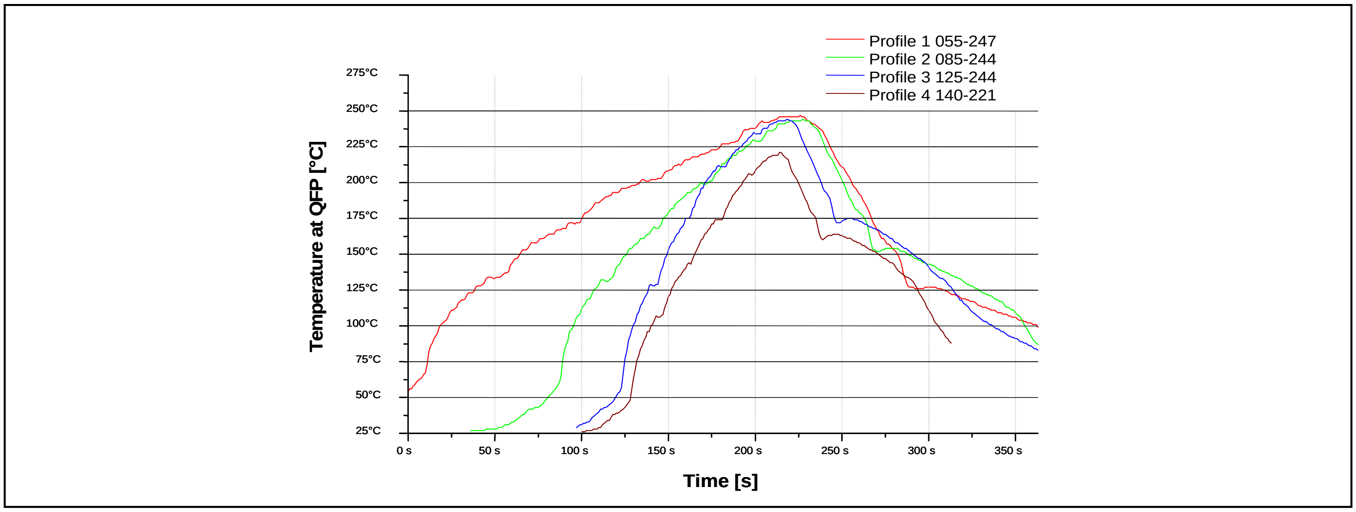



**Figure 1 - Utilized profiles (Measuring point: QFP)**

One existing PCB layout was used for testing, which had immersion tin and nickel-gold surface finishes. A total of 200 PCBs were available, which included one QFP208 and various type 1208, 0805, 0603 and 0402 chips.

For the purpose of evaluation, response variables including, amongst others, wetting area, tombstones and voids were of interest to us.

### Wetting Area

Solder paste deposits with a diameter of 5 mm were printed onto the pads selected to this end in order to determine wetting performance, i.e. the specified surface areas had a size of 19.63 square mm. Total wetted surface area was measured after reflow soldering. **Figure 2** shows an example of a measured surface.

**Figure 2 - Example of measured surface**

### Number of Tombstones

The test PCBs demonstrated tombstones on the 0402s only. .Tombstones of the type shown in **figure 3** were typical. .The tombstones were counted separately for 0402 components which were oriented parallel and perpendicular to the direction of conveyor transport. .This made it possible to evaluate any possible influence of soldering direction on tombstoning.

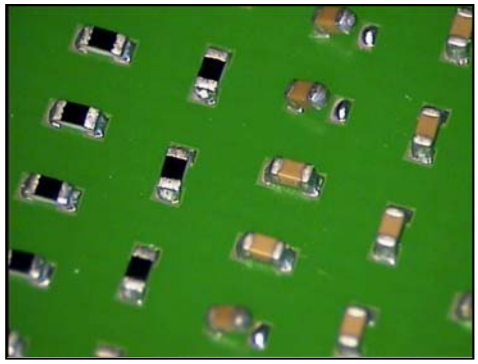
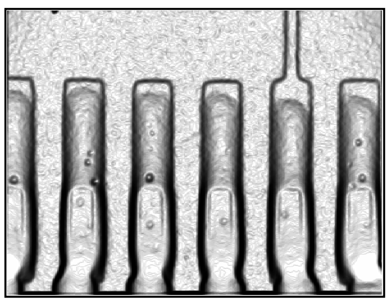


**Figure 3 - Tombstones at 0402s Parallel to Transport Direction**

**Number of Voids**
Voids were counted in the chip solder joints (1206, 0805, 0402), as well as in the QFP leads (see **figure 4**). 10 pins were inspected per QFP. Void surfaces were not acquired due to the lack or automatic evaluation.

Individual evaluation of the various chip sizes provided similar results. For this reason, results obtained for all chips were summarized, normalized and represented with the designation “voids relative”.



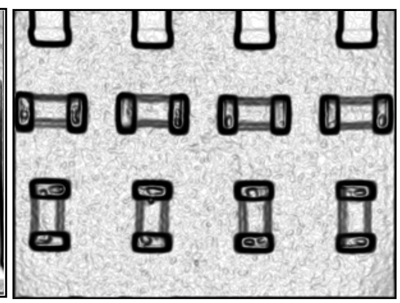


**Figure 4a - Voids in QFP Leads** **Figure 4b - Voids in Chips**

The three factors, namely solder paste, surface finish and soldering profile, could not even be characterized by a single variable parameter. For example, in addition to other parameters, the soldering profile is defined by means of preheating time, time above liquids and cooling time. Fundamentally, the soldering atmosphere can be measured, but representation in a measurable scale (≈100 ppm residual oxygen or ≈1,800,000 ppm = 18% “residual oxygen”) is not practical within this context.

This means that a classical statistical design (like a full fractional) could not be made use of, because plans of this sort necessitate variable factors. A “multi-level categorical factor plan” was used instead, for which this requirement does not exist, but certain disadvantages (no Pareto charts, no model) must be accepted as a result.

All possible factor combinations (in this case 48) must be tested for a test plan of this sort. Four PCBs were fabricated for each of these individual test combinations, so that a total of 192 PCBs were available for evaluation. In the evaluation the main effects (described with the letters A, B, C, D) and the interactions were investigated. The letter combinations describe interactions. For example, AB describes the double interaction which occurs between the solder paste and the soldering atmosphere, and ABD describes a threefold interaction amongst solder past, soldering atmosphere and temperature profile.

Probability, the so-called p value, was calculated on the basis of recorded data. This value indicates the probability with which the related change (main effect and/or interaction) to the factor (e.g. solder paste) will only result in an significant change to the examined response variable. The smaller the p value, the more certain it is that a change to the factor (e.g. solder paste) will result in a change to the response variable (e.g. tomb stoning).

**In general, the following evaluation is conducted:**

**Table 3 - Interpretation of the p-value**

| p Value | Designation | |
|---|---|---|
| > 0.05 (5%) | – | Or no designation<br>Not significant |
| 0.01 to 0.05 | * | Moderately significant |
| 0.001 to 0.01 | ** | Very significant |
| 0.0001 to 0.001 | *** | Highly significant |
| < 0.0001 | **** | Extremely significant |

**Example**:
p value = 0.0015 (e.g. for surface finish)
This means that in 99.85% of all cases it would be incorrect to claim that a change from immersion tin to nickel-gold would not result in any change to the examined response variable (e.g. wetting)!

**Results**
The main effects are used to evaluate the influence of the change to one factor on the corresponding response variable. The confidence intervals included in the graphics indicate the range within which the actual mean value can fluctuate. If the intervals overlap, there is no significant difference. In the case of interaction, the influences of mutual change to the factors (two or more) on the selected response variable are analyzed. Actually occurring interaction is represented in the diagrams by means of non-parallel straight lines.

**Table 4 - Overview of significance of the effects**

| | | Wetting Area | Tombstones (parallel) | Tombstones (perpendicular) | Voids |
|---|---|---|---|---|---|
| **Main Effects** | | | | | |
| A | Solder paste | **** | **** | *** | ** |
| B | Atmosphere | **** | **** | *** | ** |
| C | Finish | **** | | * | |
| C | Profile | **** | **** | | |
| **Interaction** | | | | | |
| AB | Solder paste – atmosphere | *** | **** | ** | |
| AC | Solder paste – surface finish | **** | | ** | **** |
| AD | Solder paste – profile | ** | **** | *** | |
| BC | Atmosphere – surface finish | | | | |
| BD | Atmosphere – profile | * | **** | ** | |
| CD | Surface finish – profile | *** | | | |
| ABC | | | | ** | |
| ABD | | * | **** | *** | |
| ACD | | | | | |
| BCD | | | | * | |

**Wetting**
**Figure 5 and 6** show the calculated primary effects of surface finish and atmosphere (including confidence intervals). A large distance between the intervals indicates high significance. Wetting increases with a nickel-gold surface finish and the use of a nitrogen atmosphere.

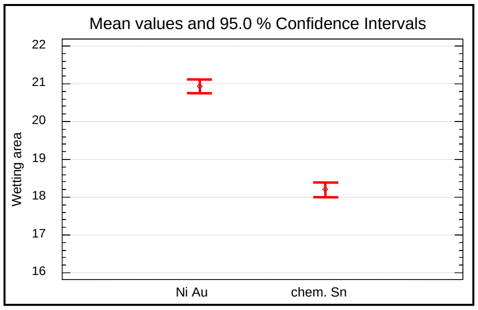



**Figure 5 - Influences resulting from Surface Finish**

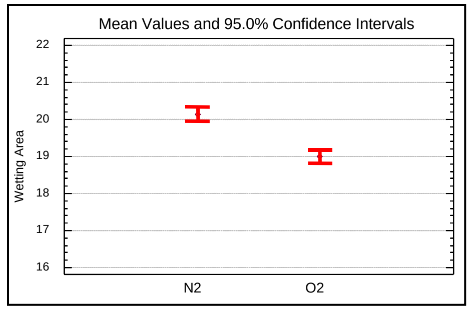



**Figure 6 - Influences resulting from the Soldering Atmosphere**

Type 1 solder paste is the best with regard to wetting area (see **figure 7**).

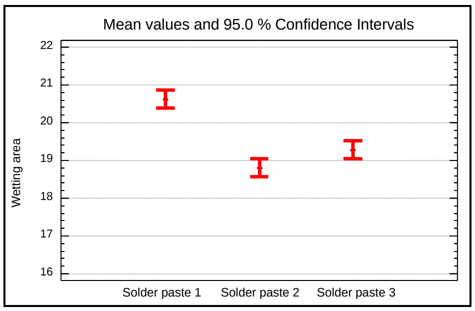



**Figure 7 - Influences resulting from Solder Paste type**

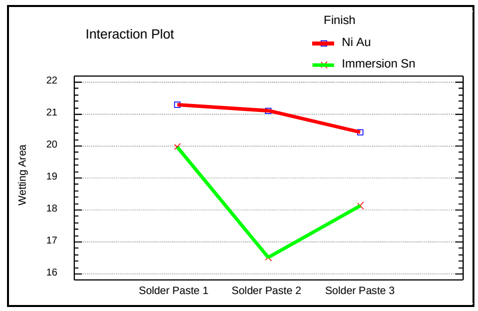



**Figure 8 - Interaction of Surface Finish and Solder Paste type**

The difference between conclusions based upon primary effects and interaction shows how important it is to analyze interaction (see **figure 8**). Type 2 solder paste spreads much more poorly on immersion tin than type 1 solder paste, but there is no difference between these two solder pastes on immersion nickel-gold.

### Tombstones

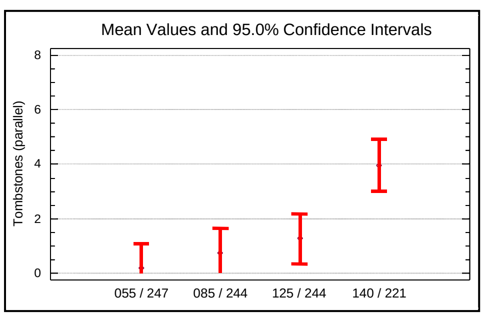
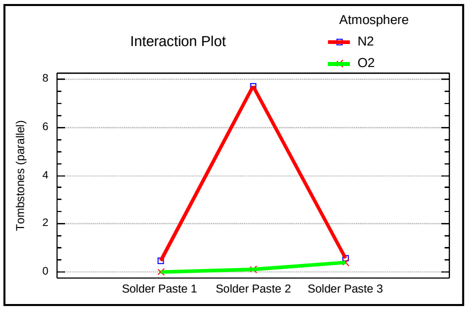



**Figure 9 - Tombstones and Profiles**

**Figure 9** shows that a fast profile promotes the occurrence of tombstones. The shorter the dwell time of the PCB in the oven, the less heat equalization occurs within the PCB, which in turn increases the probability of tombstones.

**Figure 10 and 11** demonstrate that this primary effect does not provide us with a complete picture. The combination of type 2 solder paste with a nitrogen atmosphere, as well as the combination of a fast profile with a nitrogen atmosphere, both promote the occurrence of tombstones.



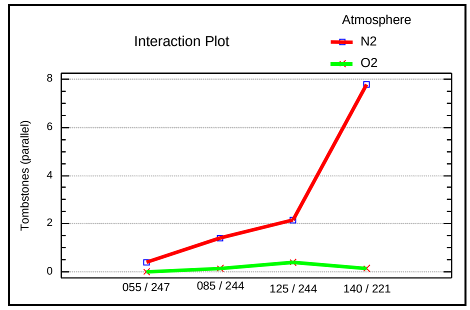




**Figure 10 - Interaction of Solder Paste and Atmosphere**

**Figure 11 - Interaction of Atmosphere and Profile**

## Voids

The type of solder paste has a very significant influence on the number of voids (see **figure 12**). Divergent interaction which occurred in some cases between the utilized solder paste and the PCB surface finish was conspicuous. Whereas the greatest number of voids occurred with type 1 solder paste on the nickel-gold surface finish, immersion tin had more voids in the case of type 2 solder paste (see **figure 14**).

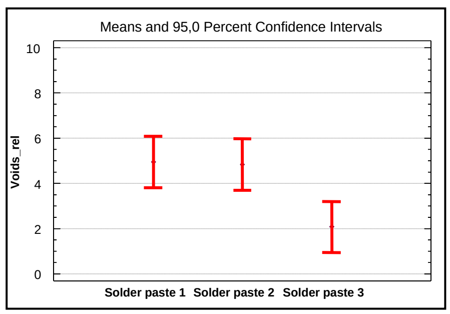
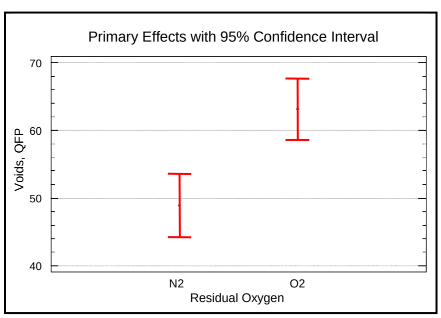



**Figure 12 - Voids and Solder Paste**



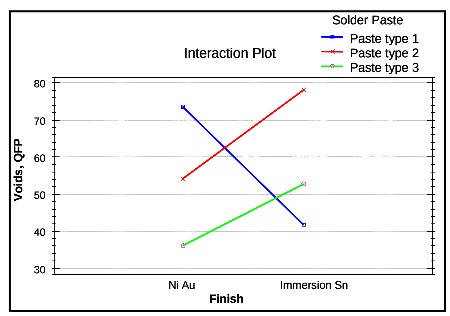




**Figure 13 - Voids and Atmosphere**

**Figure 11 - Interaction of Surface Finish and Solder Paste**

## Summary of Results

**Table 5** provides an overview of influences on the various response variables resulting from individually changed variables. The plus and minus signs indicate that the utilized material, or the corresponding "positive" or "negative" setup, has an effect on targeted results. "0" roughly corresponds to the mean value for observations made during the course of testing. More than one plus or minus sign indicate that the desired positive or negative result for the respective response variable has been more closely approached. If no entry appears, this means that the factor has no significant effects on the response variable. The number of plus or minus signs to be entered is based upon an individual evaluation.

Some of the setups contradict themselves with regard to one optimum result. For example, nitrogen is good for wetting but it promotes tombstones. The selection of a combination of setup data intended to result in best possible manufacturing quality thus always involves a compromise. In particular in the case of contradictory tendencies, additional auxiliary information is required in order to arrive at an overall optimized process.

**Table 5 - Optimized setup of factors for each response variable**

| | Wetting Area | Tombstones, parallel | Tombstones, perpendicular | Voids | Wetting Height |
|---|---|---|---|---|---|
| Paste type | | | | | |
| Paste 1 | +++ | ++ | - | - | +++ |
| Paste 2 | --- | --- | - | -- | + |
| Paste 3 | **0** | ++ | ++ | ++ | - |
| Atmosphere | | | | | |
| N2 | +++ | --- | -- | | - |
| O2 | ---- | ++ | ++ | | + |
| Finish | | | | | |
| Immersion tin | --- | | + | | - |
| NiAu | +++ | | - | | + |
| Profile | | | | | |
| 55 / 247 | **0** | ++ | - | | + |
| 85 / 244 | - | + | + | | + |
| 125 / 244 | + | - | - | | **0** |
| 140 / 221 | **0** | -- | + | | ++ |

**2. Thermal stability of moisture sensitive components during the soldering process**

A second phase of the study was dedicated to the thermal stability of various packages during the soldering process.

Package dimensions, the thickness of the mould compound over the chip, the distance of the chip and the pad from the edge of the package, and chip surface area were taken into consideration within a relatively broad spectrum in selecting the ICs. Nearly all of the components available to us had a moisture sensitive level of MSL3, and only one component (PFCM 100) was rated MSL4 (in accordance with IPC 020C). **Table 6** provides an overview of several of the examined types of ICs.

**Table 6 - Examined IC package types**

| Package Type | MSL | Storage Prior to Soldering at 30 °C, 60 % RH |
|---|---|---|
| PFCM100 | 4 | 72 hours |
| PFCM128 | 3 | 168 hours |
| PQFP64 | 3 | 168 hours |
| MQFP80 | 3 | 168 hours |
| MQFP144 | 3 | 168 hours |
| SSOP14 | 3 | 168 hours |
| SOP28 | 3 | 168 hours |
| SOT223 | 3 | 168 hours |

The objective of the study was to determine to what extent the convection, condensation (vapor phase) and vacuum-condensation soldering processes demonstrate differing degrees of influence on the thermal stability of the respective components. All of the components were removed from their moisture resistant packages before soldering, and were placed into storage for 72 or 168 hours at a temperature of 30° C and a relative humidity of 60% in accordance with their moisture sensitive levels (MSL). The components were then subjected to different reflow stressing variants as shown in **table 7**.

**Table 7 - Reflow stressing variants**

| Variant | | |
|---|---|---|
| 0 | None | (reference sample) |
| 1 | 1 x condensation | + vacuum |
| 2 | 2 x condensation | + 2 x vacuum |
| 3 | 3 x condensation | + 3 x vacuum |
| 4 | 1 x condensation | |
| 5 | 1 x convection | |

In the case of vapor phase soldering, transferred heat originates form the phase change enthalpy (gaseous → liquid). For this reason, 10 to 20 times more heat is transferred by means of this reflow process than with convection soldering, which works with hot nitrogen or hot air. Damaged components, for example delamination, are thus more likely with vapor phase soldering. A vacuum represents an additional stressing factor for moisture sensitive components.
Residual moisture increases internal pressure inside the package considerably during reflow soldering, and external vacuum increases the relative pressure difference by an additional 1 bar. This is why an emphasis was placed upon vacuum vapor phase soldering in our study. Subjecting the components to stressing three times was intended to demonstrate the ruggedness of the components, even in the case of multiple soldering.

**Figures 15 through 17** show the temperature profiles of the components for the individual reflow processes. Maximum temperature was set to 260° C for convection stressing (see **figure 15**). This corresponds to the maximum rating temperature for moisture sensitive components in accordance with the JSTD IPC 20C standard (table 4-2). The condensation soldering system was filled with Galden® HS240, which means that the maximum temperature for this process did not exceed 240° C (see **figure 16**). During the course of adaptive vacuum stressing, a final pressure of ≤ 10 mbar was achieved for a period of approximately 30 seconds (see **figure 17**).

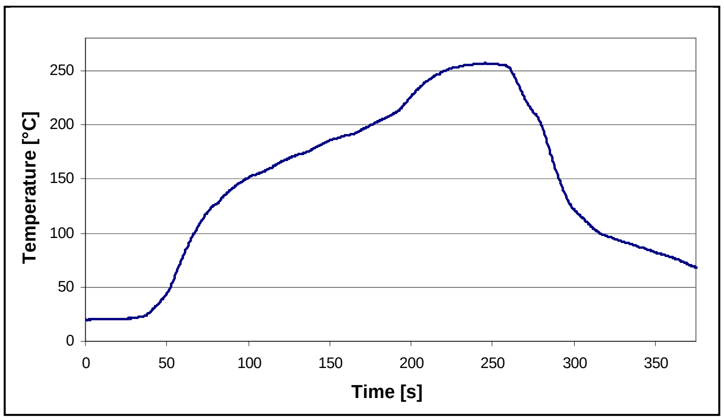



**Figure 15 - Convection Stressing**

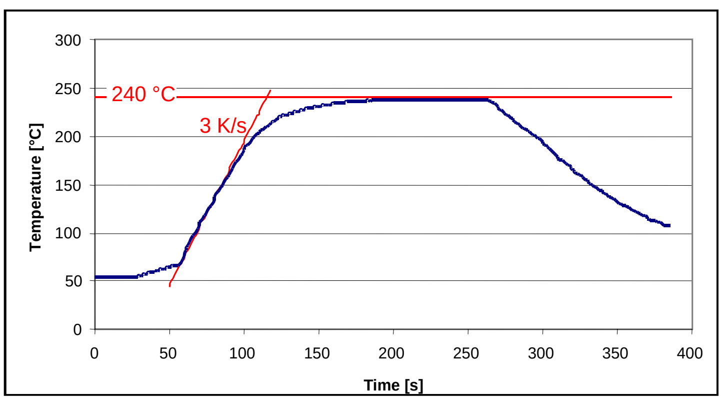



**Figure 16 - Condensation Stressing (Vapor Phase) without vacuum**

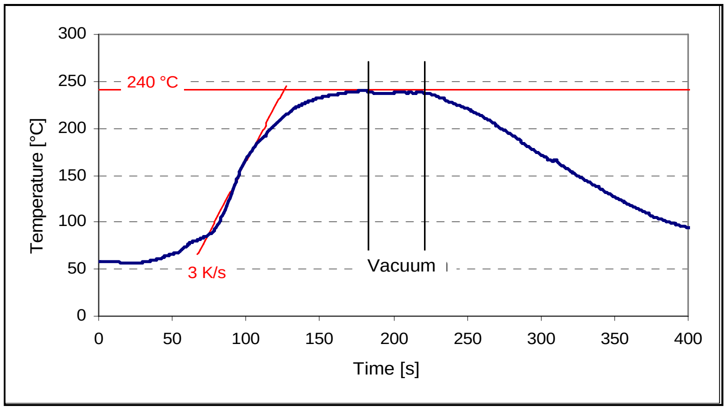
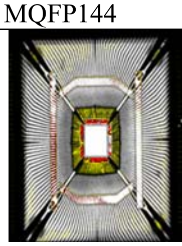
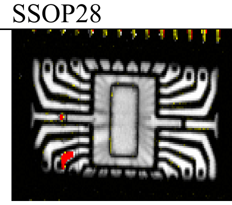
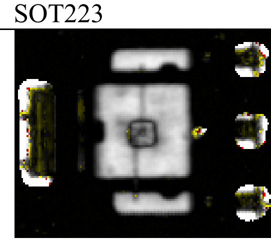
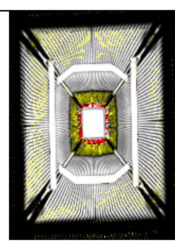
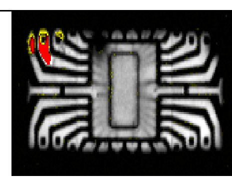
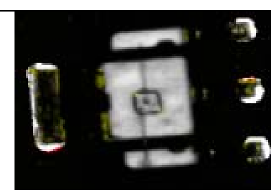



**Figure 17 - Condensation Stressing (Vapor Phase) with vacuum**

After respective thermal stressing, the components were examined with an ultrasonic microscope using the pulse-echo technique (C-scan).

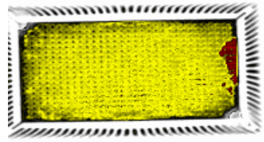
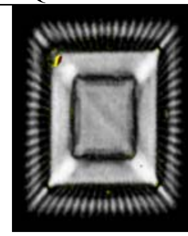
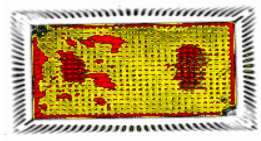
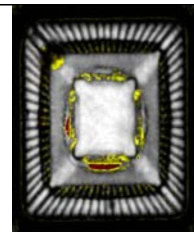
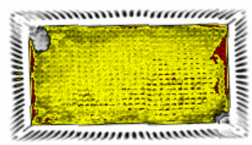
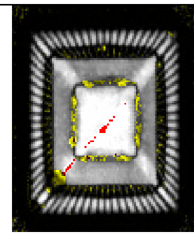
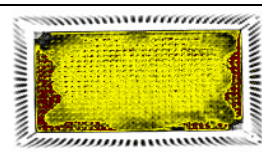
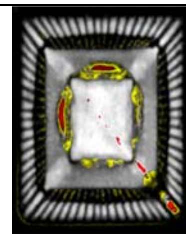
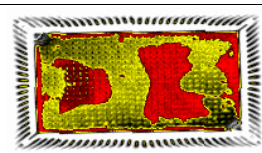
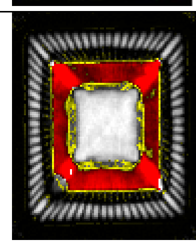
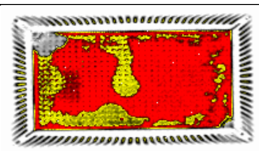
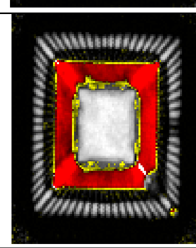
**Results**

**Table 8 - Ultrasonic images of the SSOP28 and the SOT223 before and after reflow stressing**

| | MQFP144 | SSOP28 | SOT223 |
|---|---|---|---|
| Reference without reflow |  |  |  |
| 3 x condensation + vacuum |  |  |  |

The examined SSOP and SOT components have very rugged packages, which didn't demonstrate any delamination even after being subjected to reflow stressing several times. The MQFP80 and MQFP144 packages proved every bit as rugged.
As opposed to this, the PQFP64 already demonstrated slight delamination after convection soldering, as well as after convection soldering without vacuum, although the bottom of the chip carrier did not demonstrate any changes at all. Delamination at the chip carrier/mold compound level increases as soldering stress becomes greater, and spreads out over the entire surface of the pad. 90% of all tested PQFP64 packages failed after being subjected to vacuum condensation soldering twice.

**Table 9 - Ultrasonic images of the PFCM100 before and after reflow stressing (interposer level)**

| | PFCM100 | PQFP64 |
|---|---|---|
| Reference |  |  |
| Convection |  |  |
| 1 x condensation |  |  |
| 1 x condensation + vacuum |  |  |
| 2 x condensation + vacuum |  |  |
| 3 x condensation + vacuum |  |  |

Sensitivity to reflow stressing also increases with more complex package designs, which has been substantiated, for example, by means of the examined PFCM128. The chips on the ICs are bonded to interposers, which in turn are mounted to the middle pad of the lead frame. Delamination at the interposer/lead frame level becomes apparent to an ever greater extent as reflow stress increases. Convection soldering demonstrates defect patterns which are similar to those of condensation soldering without vacuum. The component is destroyed when subjected to reflow stressing several times with vacuum. With regard to thermal stability during the soldering process, there was no difference between the PFCM100 with a moisture sensitive level of MSL4 and a PFCM128 of comparable design with a moisture sensitive level of MSL3. These results underscore the fact that thermal stability during the soldering process is not characterized by the degree of sensitivity to moisture.

**Summary**

As regards thermal stability during the soldering process, the various components demonstrate greatly varying performance. Whereas SSOP and SOT packages have proven themselves quite rugged even when subjected to reflow stressing several times, delamination is apparent at more complex components after being subjected to stressing only once. As the number of soldering processes increases, more and more delamination occurs, and the component is thus destroyed.

The effects of on-time only convection soldering are quite comparable to those of condensation soldering without vacuum. Very minimal, or no changes at all can be substantiated in the packages.

As expected, multiple soldering and additional vacuum processes result in considerable stressing for certain package designs. For this reason, thermal stability during the soldering process should be taken into consideration prior to soldering, in addition to strict adherence to MSL compatible processing of the components. The moisture sensitive level is only characteristic of the package's moisture class in accordance with JEDEC IPC 020C, but has nothing to do with its thermal stability during the soldering process, which should be requested from the manufacturer in any case.