

Implementation of Lead-Free Wave Soldering Process

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Abstract

Test series with different wave soldering parameters were run to examine the solder quality achieved in a lead-free wave soldering process. The solder was a Sn-Ag-Cu (SAC) alloy. Solder pot temperature was set between 250°C and 275°C. The most often used pot temperature was 260°C, which is the pot temperature usually used with SAC solders. Other examined process parameters were the solder contact time, soldering atmosphere, preheating temperatures, flux type and flux amount. The test series included different lead-free PCB finishes. Solder bridges and unsoldered SMD components were often observed likely due to the higher surface tension of the SAC alloy. By optimizing the soldering process the amount of these defects can be minimized. One of the main problems observed in lead-free wave soldering was the difficulty to solder through-hole components with a large thermal mass. Typically components with a large thermal mass could be soldered only with long solder contact times and high solder temperatures. Visible defects on the components were rarely observed, even when using these extreme thermal set values. Fillet lifting phenomena was observed in the through-hole joints when cross sectional analysis was accomplished.

Solder composition was analyzed regularly. Special attention was paid to possible increase in copper or lead content. SAC alloys leach PCB copper faster than tin-lead solder. Copper dissolved from PCBs increases the copper content in a solder. The test series contained partly electronics assemblies with tin-lead terminated components. Tin-lead terminated components are a possible source of lead contamination of lead-free solder. A significant risk to lead contamination is posed also if lead contaminated tools are used in solder pot maintenance, like in removing dross. Analyses revealed no significant increase in copper or lead content during the test series, probably because the amount of soldered PCBs was low compared to production volumes.

Keywords: lead-free wave soldering, solder contamination, pot temperature, solder contact time, through-hole filling, fillet lifting

1. Introduction

Potential health hazards and toxicity of lead has encouraged lead to be removed from many applications, like fuel additives, piping, paints and now from electronic products too. Lead is used in electronic products as a constituent of solder, but also components and printed circuit board (PCB) finishes may contain lead. The European Union directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) [1] bans the use of lead from 1 July 2006. Changing to lead-free solder has many impacts in wave soldering process though there are also similarities between traditional and lead free wave soldering process [6],[7]. Tin-lead and SAC process are subject to many similar solder defects. Moreover, many of the defects found on SAC solder can be remedied with the same methods as those found on tin-lead solder. For example, if tin bridges can be reduced by a change in solder wave and circuit board travel rates in tin-lead process, so can they be reduced in SAC process. On the other hand there are solder defects like fillet lifting, which is common on SAC solder and only rarely observed with tin-lead solder. Furthermore, solder bridges and unsoldered SMD components are often observed likely due to the higher surface tension of the SAC alloy

SAC process is optimized principally the same way as tin-lead process. However, the set values for tin-lead solder are not directly applicable to SAC process. The two main differing parameters are the solder temperature and the solder contact time. If contact time is too short and/or solder temperature too low especially through-hole components with large thermal mass will be incompletely soldered. Usually solder temperature of 260°C is used in lead-free wave soldering process. The lower heating over the solder melting point compared to tin-lead solder is compensated by using longer solder contact time.

On the basis of our results, it cannot be shown that SAC process could be optimized as well as tin-lead process with respect to solder defects. It should be borne in mind that the process window for SAC process is narrower than that for tin-lead solder. Due to solder melting point, SAC process operates much closer to component failure limit, giving a smaller manoeuvring space.

The results presented in this study are results from the research project called "Implementation of Lead-free Wave Soldering Process (Aapeli)" executed in years 2002-2003 and funded by the National Technology Agency (TEKES) and Finnish electronics industry[14],[15]. There were 12 Finnish electronics manufacturing companies as participants in this research project. From every participant there was soldered a test serie containing some tens or hundreds of test PCBs. On that way a large number of PCBs could be soldered and more comprehensive view on lead-free wave soldering was achieved. Test series were run on a Vitronics Soltec Delta 6622 wave soldering machine equipment with a spray-nozzle fluxer and a three-stage preheater. The used SAC alloy composition was Sn3.0%Ag0.5%Cu.

2. Changeover to lead-free wave soldering process

Both tin-lead and lead-free wave soldering may be used in the same factory during the transition period. Over that time, caution must be taken to prevent solders from mixing with one another. Each of the two processes requires separate and well-marked tools so that no tin-lead solder will be transferred to the pot for lead-free solder and vice versa. On adding solder, the operator must make sure that no tin-lead bars are accidentally put in the solder pot for lead-free solder and vice versa. By no means every solder bar has its composition marked over it. Solder bars of different materials should therefore be stored well apart or have their composition clearly marked over the packaging.

Since solder metals are extracted from ore, lead-free solder will contain impurities. The cleaner solder is desired, the more it will cost to purify it. It is not easy to regulate solder composition under solder production, and the final composition cannot be established until a solder batch is ready. A solder batch obtained by *Elektroniikan 3K-tehdas* had a lead content of 0.03%. There is no official standard or legislation as to the maximum lead content of lead-free solders for the moment. The proposed maximum lead content for the RoHS directive is 0.1%. If lead-free wave soldering process has been contaminated by lead over solder substitution or solder transition, lead having dissolved into the solder pot from components and circuit boards under soldering, the proposed limit may entail problems. If the process has been contaminated and the applied solder contains 0.1% of lead, the lead concentration will not considerably lessen in the solder pot, even if new solder is introduced into it. Almost whole solder volume ought to be changed, which would be a remarkable expensive action.

Common lead free solders used in wave soldering are SAC alloys melting at circa 217°C and a Sn0.7%Cu solder melting at circa 227°C. There may also be added nickel on Sn0.7%Cu solder [11]. Nickel containing Sn0.7%Cu solder is patented by Nihon Superior [9][10] and is offered to market under brand name "Sn100C" [11]. An advantage of Sn0.7%Cu solder is lower price compared to silver containing SAC alloys. SAC alloys are a Sn-Ag-Cu solder family, where Ag content is between 3.0% and 4.0% and copper content between 0.5% and 0.9%. The SAC eutectic composition determined by U.R. Kattner et al. is Sn3.5%±0.3Ag0.9%±0.2%Cu [12]. High tolerance values in the determined eutectic composition must be noticed. More accurate eutectic composition for the SAC alloy could not have been so far measured. The SAC alloy used in this research was Sn3.0%Ag0.5%Cu, which means that it is a hypoeutectic SAC alloy or in other words, silver content in this alloy is slightly under the eutectic composition. An analysis result of the SAC alloy used in this research is listed in table 1. Other possible SAC alloys are for example Sn3.5%Ag0.7%Cu and Sn3.9%Ag0.6%Cu (a hypereutectic alloy). For the present, it can not have been evidenced that there would be that kind difference between those alloys that it would have meaning in the practical soldering process. Anyhow, the difference between the SAC alloys is under investigation and there are also researches, which have shown differences between SAC alloys. For example K.S. Kim et al. have reported that there may be formed less large primary Ag₃Sn precipitates in hypoeutectic SAC alloy than in other SAC alloys, depending though on the cooling rate of the alloy. [13]. Large primary Ag₃Sn may have an influence on the ductility of an alloy. Follow-up research will show the significance of those differences.

Table 1. An analysis from the SAC alloy used in this research. The elements were analyzed by an atomic absorption spectrometer (AAS).

| Element | Content [%] | Limits of error +/- in analysis |
|---------|-------------|---------------------------------|
| Bi | 0.01 | 0,0013 |
| Cu | 0.52 | 0,0066 |
| Sb | 0.01 | 0,0251 |
| Fe | <0.01 | 0,0010 |
| Pb | 0.06 | 0,01 |
| Ag | 3.13 | 0,0400 |
| Sn | bal. | - |
| Al | <0.003 | 0,0010 |
| Ni | <0.003 | 0,0014 |
| Au | <0.01 | 0,0002 |
| Cd | <0.001 | 0,00005 |
| Zn | <0.001 | 0,0002 |
| As | <0.01 | 0,0052 |

During the research project solder and dross was analysed regularly. Dross was analyzed to observe if solder and dross composition differ from each other. The intermetallics between tin and copper like Sn_6Cu_5 are heavier than SAC solder. This means that Sn_6Cu_5 intermetallics will not float on the solder surface like it was the case with tin-lead solder. It is assumed that intermetallics heavier than solder will sink to the bottom of solder pot and on that way copper would not be removed with dross removal in the same proportion as there is copper in the solder. On that way copper concentration would increase. Copper concentration as a function of time is presented in Fig 1 and silver concentration in Fig. 2. As it is noticed from figures 1 and 2, there are no remarkable difference between solder and dross composition. It can be noticed from figures 1 and 2 also that silver and copper content has stayed constant during the research project. For example, there can be seen any ascending or descending trend in silver or copper content. Copper will dissolve from the component leads and PCBs, but the amount of soldered PCBs (some thousands) was so low that a difference for example in copper content can not be noticed.

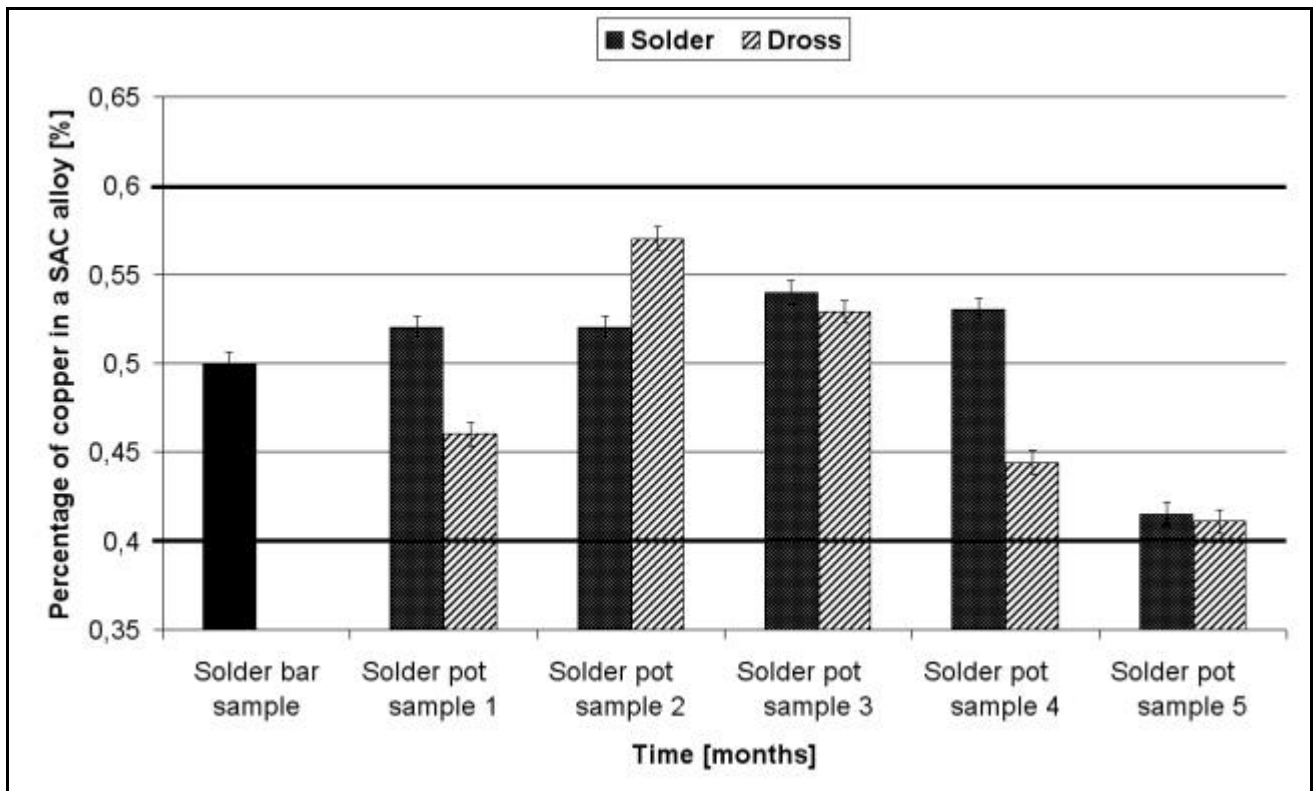


Fig 1. The percentage of copper in a Sn3.0%Ag0.5%Cu solder and in dross formed from this SAC solder. The limit values for copper content in this SAC solder are 0,4% (min) and 0,6% (max).

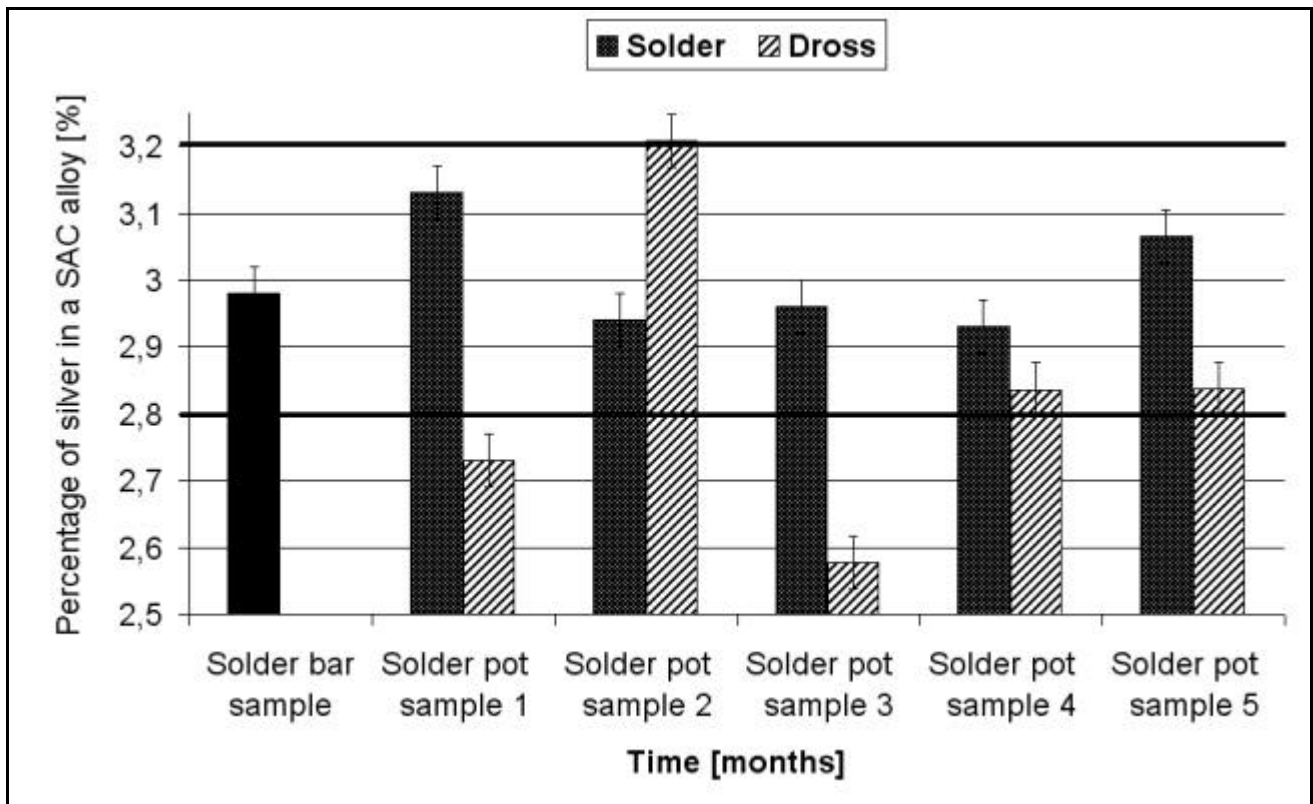


Fig 2. The percentage of silver in a Sn3.0%Ag0.5%Cu solder and in dross formed from this SAC solder. The limit values for silver content in this SAC solder are 2,8% (min) and 3,2% (max).

There is presented the lead content during the research project in figure 3. The solder bar contained about 0,03% lead. When changing soldering machine to lead-free, only solder pot was changed. The solder nozzles were cleaned by hot air blower as good as it was possible. Anyway, when the solder was added to the soldering machine, it contaminated with lead, which was left on solder nozzles. After adding the solder to solder pot, the lead content was 0,06%. After that there was no change in lead content (fig. 3) though also tin-lead terminated components were included assemblies soldered during this research project.

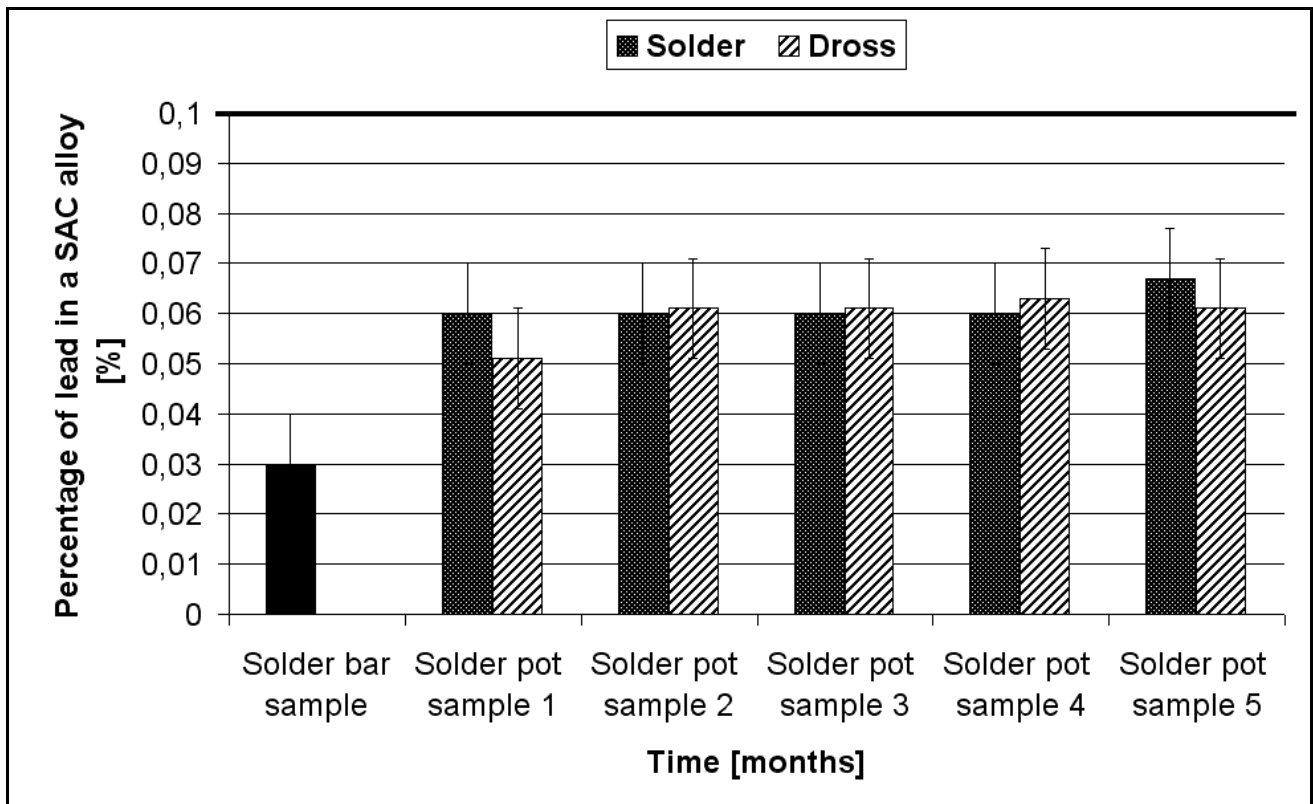


Fig 3. The percentage of lead in a Sn3.0%Ag0.5%Cu solder and in dross formed from this SAC alloy. The maximum concentration value of lead proposed for RoHS directive is 0,1% by weight in homogenous materials of electrical and electronic equipment.

Lead-free solders may cause severe corrosion to materials used in wave soldering machines. Different solutions to prevent material degradation are for example titanium construction, nitrided stainless steel, melonite QPQ coating, ceramic coated stainless steel and cast grey iron [5]. The solder pot used during the research project was coated to withstand the eroding impact of lead-free solder. Anyway, the nickel concentration of solder was measured so that it could be observed if there is dissolution of nozzle or pot material [4]. There were observed no change in nickel concentration.

3. Differences between SnPb and SAC processes

3.1. Solder temperature

It is almost inevitable that solder temperature should be raised from value used in tin-lead process.. At solder pot temperatures for tin-lead process, lead-free soldering is either impossible or calls for an extremely long solder contact time. The contrast between solder pot temperatures is not as great as between solder melting points. Instead of raising temperature unduly, the solder pot temperature should be raised moderately, while the solder contact time should be lengthened. We ran tests at solder pot temperatures ranging from 250°C to 275°C, and even 250°C imparted good quality, given a long solder contact time and assemblies with minor thermal mass and minor thermal mass variation.

3.2. Solder contact time

It is typical that too short a contact time results in incompletely soldered pin-through-holes. Wetting time can be shortened by raising solder temperature, but this will increase thermal stress to components.

3.3. Fillet lifting phenomenon

The results find that the soldering quality produced by an optimized SAC process fails to differ from that produced by a tin-lead (SnPb) process with regard to visually observable solder defects, excepting a duller surface appearance. On the other hand lead-free solder is subject to solder defects alien to tin-lead, for example fillet lifting. Fillet lifting is a solder cracking phenomenon, where solder fillet is lifted from the edge. This defect is not visible to the naked eye. One way of identifying fillet lifting is by examining the solder joint in cross-section by an electron microscope. Figure 4 and figure 5 show fillet lifting and a closely related phenomenon, tearing. Pad lifting (fig 6) was also observed in test PCBs. Examined PCBs were produced by two PCB manufacturers. Pad lifting was observed only on the PCBs of the other PCB manufacturer. It was assumed that copper pad contact to laminate surface was weaker on PCBs of this PCB manufacturer than the other manufacturer. Based on this, pad lifting may be avoided by modifying PCB manufacturing process.

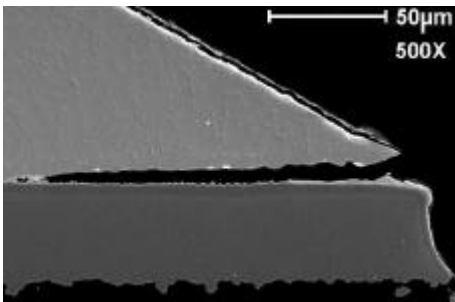


Fig 4. Fillet lifting: solder joint edge breaks off and lifts from the pad under soldering.

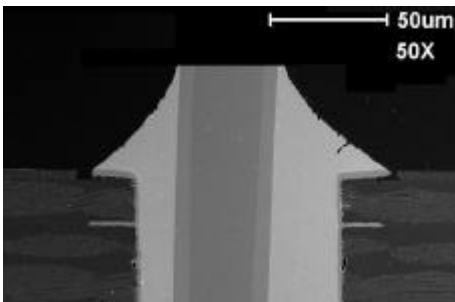


Fig 5. Tearing: solder does not break off at the solder edge but elsewhere between the two edges.

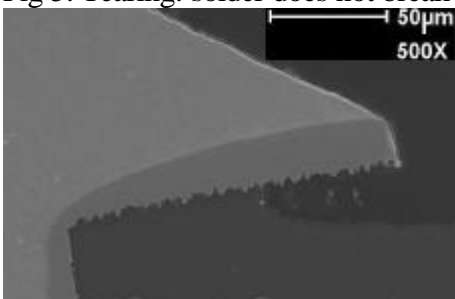


Fig. 6. Pad lifting: Pad is lifts up from the PCB surface.

Fillet lifting phenomena are commonly observed [2]:

- in high-Sn alloys, including Sn3.5Ag but not observed in eutectic SnPb and SnBi (tin-bismuth).
- with pasty alloys
- lead-free solders contaminated with lead: 1 percent lead will lower the solidus of tin-silver (SnAg) from 221°C to 179°C
- typically in wave soldering, and occasionally at reflow soldering

In this research the fillet lifting phenomenon was observed even when lead-free components were used. In that case solder was the only possible source of lead. Moreover, lead content in the solder used in this research may be regarded as low (0,06%). This amount of lead is a typical impurity level for lead in lead-free solders. Thus, it is evidenced by this research, that the fillet lifting phenomenon is met with lead free SAC solders without any additional lead contamination in solder joint.

3.4. Other, less significant or vague differences

A typical temperature profile measured in a lead-free wave soldering process is presented in Fig 7. It is often recommended that a lead-free wave soldering process should have a slightly higher preheating temperature in order to mitigate thermal shock. On raising temperature, caution should be taken against deactivating flux prematurely. A rise in temperature subjects components to greater thermal stress. It should be weighed, whether it is the higher preheating temperature or the greater thermal shock that has the more adverse effect.

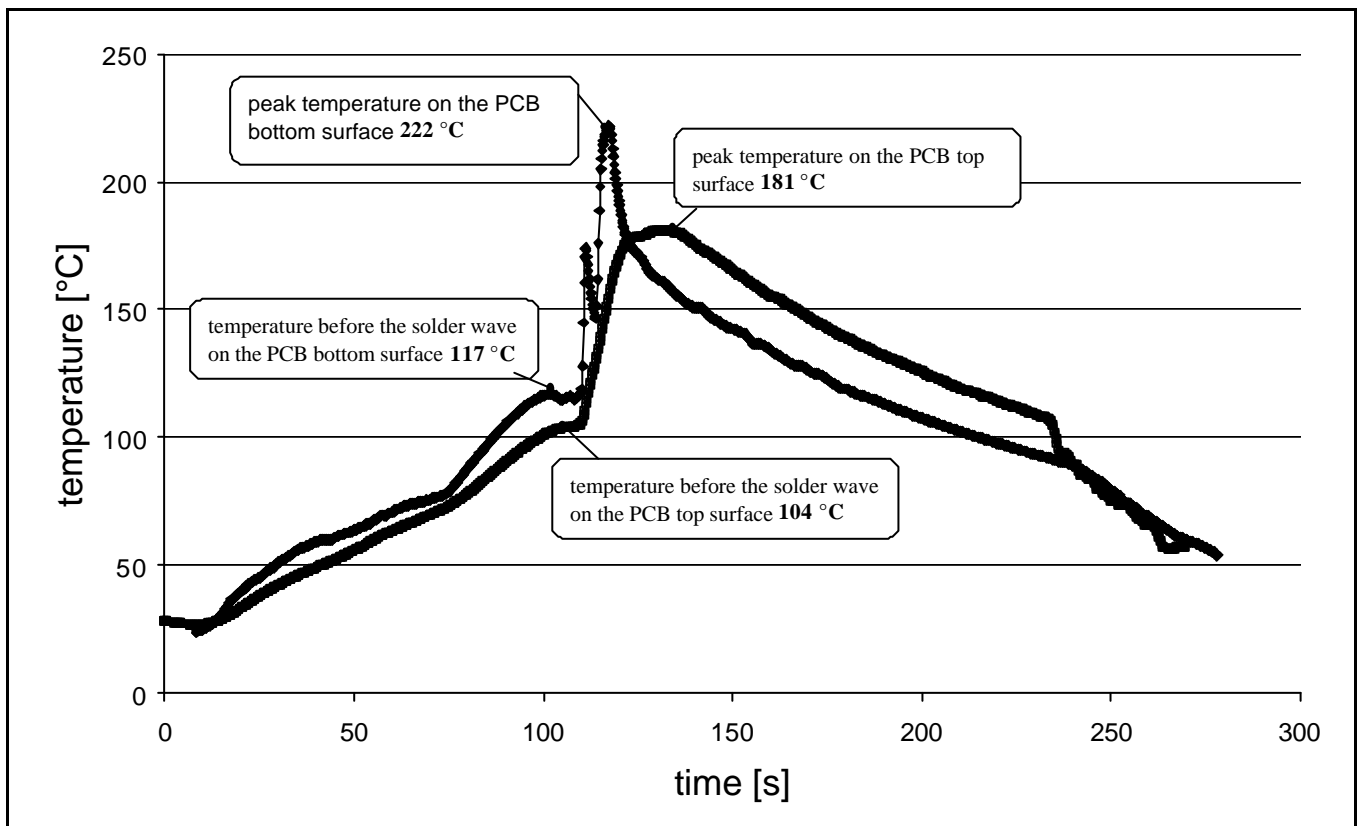


Fig. 7. A typical temperature profile measured in a wave soldering process on a double sided FR-4 PCB.

Special fluxes that are compatible with lead-free solders are being marketed for lead-free wave soldering. Fluxes not designed for lead-free processes, i.e. fluxes that have a long history in tin-lead process, were also used to solder test series boards in the course of this research. Details of different fluxes used in test series are listed in table 2. The soldering quality achieved with fluxes designed for the traditional tin-lead soldering process was reasonable. It was not observed that a flux designed for tin-lead would for example char on a PCB surface in lead-free temperatures. Anyhow, with fluxes specially designed for lead-free process was achieved better soldering quality than with fluxes designed for tin-lead process. Better soldering quality with fluxes designed for lead-free process may originate from the fact that there are usually a higher solids content and higher acid value in fluxes designed for lead-free process. Even though high acid value flux wets better, its residue may turn into a problem in the long run, for example by starting to corrode. The activity of flux residues must always be secured when using a new flux.

Table 2. Used fluxes (all no-clean).

| Flux | producer | Alcohol-based / VOC-free | Acid value [mg KOH/g] | Solids content [%] | Recommended PCB temperature prior to wave[° C] |
|------|----------|--------------------------|-----------------------|--------------------|--|
| F1 | V1 | alc | 14.7±0.5 | 2.4 | 87-115 (top) |
| F2 | V2 | alc | 14-16 | 1.8 | 100-130 |
| F3 | V2 | alc | 28-30 | 3.5±0.1 | 100-165 (top) |
| F4 | V4 | alc | 18 | ? | 85-110 |
| F5 | V5 | alc | 15.0 | 2.8 | 100-110 (bottom) |
| F6 | V5 | alc | 19.9 | 3.1 | ? |
| F7 | V5 | alc | 25.7±1.0 | 4.0±1.0 | ? |
| F8 | V1 | VOC-free | 35.9±1 | 4.25±0.5 | 90-125 (top) |
| F9 | V6 | VOC-free | 35.6±2.0 | 4 | 93-104 (top) |
| F10 | V7 | VOC-free | 50-54 | 8 | 105-115 |

4. Optimizing the lead-free wave soldering process (a case study)

Several boards in the test series suffered from poor through-hole filling. At first we assumed that the machine spray fluxer failed to operate to standards and that pin-through-holes were inadequately fluxed. By fixing a thermally sensitive fax paper on top of a board and passing the board through fluxing, it was nevertheless found that sufficient amounts of flux were being dispensed in pin-through-holes by the fluxer. As evidence, the fax paper was discoloured over areas covered by pin-through-holes.

We found that a longer contact time or higher solder temperature were the most effective means against incompletely pin-through-holes. Since it is likely that components of high thermal mass are just not hot enough for forming a solder joint, soldering area temperature can be raised by increasing time or temperature in such a way that soldering will occur.

To clarify the influence of different wave soldering parameters on soldering quality of pin-through holes there were soldered test PCBs with different setting values. The test board was technically easy to solder and the pin-through-hole solderability was the only major shortcoming. With same parameters there were soldered always 6 boards to eliminate the influence of random variation on soldering quality. When designing the experiments (DOE) different tools, like the Taguchi method, may turn out to be useful [3], [8]. We evaluated the soldering quality by a simple method calculating the incompletely soldered through-hole pins. We obtained a high soldering quality of

pin-through-holes (0 or 1 incompletely soldered pin-through-holes per board) by using the following set values:

- flux: alcohol-based and VOC-free
- solder pot temperature: 250°C and 260°C
- contact time: 2s, 4s and 6s
- soldering atmosphere: nitrogen/air
- flux volume: 40 Hz¹, 80 Hz and 120 Hz

and the following parameter combinations.

- pot 260 °C, dwell time 4 or 6 sec
- pot 250°C, dwell time 6 sec

We obtained a poor soldering quality of pin-through-holes (40 or more incompletely soldered pin-through-holes per board) by using the following parameter combination.

- pot 250 °C, dwell time 2 sec

Neither flux type (alcohol-based/VOC-free) nor soldering atmosphere (nitrogen/air) influenced the soldering quality of the pin-through-holes to considerable extent. Flux amount has no remarkable influence on the solderability of pin-through-holes, when there was just enough flux. Excess alcohol based flux was not observed to have any negative influence on soldering quality except for increased flux residues amount. After dispensing extensive amount of water-based flux, large cavities of 0,4-0,6 mm in diameter were observed on solder surfaces by the naked eye. The water (aka thinner) had probably not evaporated prior to the wave, thus giving rise to blow holes on solder surfaces.

There was also accomplished a similar test with another test board where different preheating temperatures and a solder pot temperature 275°C were included. Temperatures on PCB surface just before the soldering wave was set at 100°C, 110°C and 125°C in that test. It was observed that preheating temperatures (100°C...125°C) has no remarkable influence on solder hole filling. With solder temperature 275°C components even with high thermal mass were soldered completely. This means, that the soldering temperature and the solder contact time have the greatest impact on through-hole filling.

5. Components and circuit boards in lead-free wave soldering

Different assembly types were soldered in the course of the test series. Circuit board laminate was the normal flame retardant type 4 (FR-4), except for two test series, where it was composite epoxy material type 1 (CEM-1). FR-4 is a glass fiber epoxy laminate. CEM-1 is a paper based laminate with one layer of woven glass fabric. CEM-1 laminates are not suitable for plated through-holes but on the other hand they are low in cost. As CEM-1 boards come in a number of types, their glass transition points tend to show variation. In our test series, CEM-1 board glass transition point was circa 130°C, in contrast to 140°C of a standard FR-4 board.

Circuit board warpage was not measured. Even so, it was noticed by visual inspection that the boards had not undergone remarkable warpage over lead-free process, unless there were exceptional heavy components on a board. There must be paid a special attention on the PCB support during soldering in lead-free wave soldering process. CEM-1 boards were also successfully soldered in

¹ Flux volume is adjusted by flux pump speed, which has hertz (Hz) as a unit. Higher speed means more flux on the PCB.

SAC process. Although a total of 75 CEM-1 boards were soldered, only one was identified with inter-layer delamination. We have no knowledge as to whether this delamination was specifically caused by the higher thermal stress imparted by SAC process, or whether this could have happened in tin-lead process. Anyhow, higher soldering temperatures tend to increase the likelihood of delamination.

Owing to the sheer number of test series, the number of various component types in our test series may be looked upon as considerable. It was seen by visual inspection that the high temperature of SAC process did not inflict damage to mounted components in the main. An exception was made by a plastic connector, partially melted and given away by long strands of plastic. The melting was such that the connector could still work as intended. Components were not subjected to electrical testing in the course of this research.

6. Conclusions

On the basis of our results, SAC process can be optimized as well as tin-lead process with respect to normal solder defects. It should be borne in mind that the process window for SAC process is narrower than that for tin-lead solder.

A poor through hole filling was one of the main problems often met when soldering wave soldering test series. The different soldering parameters were investigated to find out, which parameters have the most remarkable influence on through-hole filling. Evaluated process parameters were flux type (alcohol/water based), flux amount, solder temperature (250°C, 260°C, 275°C), solder contact time (2 s, 4 s, 6 s), preheating temperature (100°C, 110°C, 125°C) and soldering atmosphere (nitrogen/air). It was observed that the solder temperature and the solder contact time have the greatest impact on through hole filling. Other process parameters have influence on through-hole filling, but their impact is minor compared to the solder temperature and the solder contact time. A usual solder temperature used in lead-free wave soldering process is 260°C. Based on the results, it is high enough temperature in many cases supposing that the solder contact time is long enough.

A special defect detected in lead-free wave soldering is the fillet lifting phenomenon. Based on results, fillet lifting phenomena are met in a lead-free wave soldering process even without any other lead contamination than what is as an impurity in lead-free solder. If pad lifting phenomena occur, the reason is likely to be a poor copper pad contact on the PCB laminate.

There were different PCB assemblies included in soldered test series. There were both lead-free and tin-lead terminated components on assemblies. Most of the components were the same as used in tin-lead process, which means that their plastics were not designed to bear higher temperatures of lead-free process. Despite of that, thermal damages were rarely seen on components by visual or X-ray inspection. PCB laminates were usually the normal FR-4, but there were also CEM-1 laminates soldered in lead-free wave soldering process. Contrary to some preconceptions, even CEM-1 laminates could be soldered successfully in lead-free wave soldering process. However, from the soldered 75 CEM-1 PCBs one suffered from delamination. It could not be tracked down, whether the delamination was caused by the higher soldering temperatures or whether this PCB was invalid already before soldering. Remarkable warpage of PCBs consisting of both FR-4 and CEM-1 laminates was observed only when boards with heavy components were soldered. There must be paid a special attention on the PCB support during soldering in lead-free wave soldering process.

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