Practical Experience in Lead-free Wave Soldering

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Summary

The introduction of lead-free solders in the electronics industry has become a great challenge to the users and manufacturers of production facilities and materials. The interaction of module, material and soldering system is particularly complex when it comes to wave soldering techniques and requires exceptional care during the development of secure processes. The experiences described in the following article refer to a three-year real-life test of lead-free wave soldering in normal atmosphere and two-shift production.

We present the internationally recommended substitute alloys and explain the wave soldering systems adjustments regarding fluxers, preheating system and soldering module. Our main issue is the choice of appropriate materials for the soldering module.

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The introduction of lead-free solders in the electronics industry has become a great challenge to all those involved in the production process. The interaction of module, material and soldering system is particularly complex when it comes to wave soldering techniques and requires exceptional care during the development of secure processes. The experiences described in the following article refer to a three-year real-life test of lead-free wave soldering in normal atmosphere and two-shift production.

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1. Alloys

Based on international recommendations and today’s know-how, the future substitute alloy for SnPb will be highly tin-bearing alloys with silver and/or copper as secondary elements.
The recommendations refer to the following alloys:

Alloy	SnCu0.7	SnAg3.5	SnAg3.xCu0.x
Melting point	227°C	221°C	217°C

Basically, all of the above alloys are suitable for the wave soldering process. Processing of these solders in real life, however, is a lot more sophisticated than that of the comparable SnPb alloy.

The SnCu alloy shows very good flow characteristics at just a few degrees above the melting point. Its disadvantage is the fast dissolution rate of component metallizations on a silver – palladium basis. The SnAg alloy, on the other hand, produces a high-viscosity oxide film on the solder wave surface which affects the flow properties of the solder. That is why these alloys were rejected by the test user.
The SnAgCu alloy seems to be the best alternative with regard to dissolution rate and melting point but is also more expensive than the other two. Quality and reliability of the joints soldered with the above alloys are similar to SnPb. The tests on the effects of various LP surface metallizations, however, have not yet been concluded. The practical test was carried out with SnAg3,8Cu0,7 alloy.
The wetting speed of the solders is a bit lower than that of SnPb, i.e. wave soldering requires either a longer wetting time or higher temperatures.

Considering the PCB and component metallization, we also have to take the generation of multimaterial alloys in the soldering joint into account when we choose a substitute alloy. From the metallurgical point of view, only binary and ternary systems can be illustrated in the phase diagram. If, via metallization of the LP or the component, additional elements get into the solder, these alloys can no longer be illustrated in a phase diagram and may hide unwanted surprises regarding the long-term behaviour of the soldered joint.

2. Soldering System

If we compare reflow and wave soldering process we realize that the number of influencing machine parameters during wave soldering is many times the amount of that during reflow soldering.

This fact inflates the matrix of possible parameter variations and combinations. In reality, the mutual influence and dependence can be demonstrated only by large-scale test series. If we also consider component metallization and LP surface, the development of a secure process becomes ever more extensive.

2.1 Flux Module

In innovative wave soldering systems, the flux is applied by means of spray fluxers. This type of application has become standard and corresponds to the latest technology. The great advantage of the spray fluxers is their closed structure and the application of exclusively new flux – reproducible and quantity-defined - on the board.
The modified conditions of the overall process should be decisive when choosing the flux. Most important the longer wetting times and higher temperatures of the soldering. Both lead to a fast or premature flux activator consumption. If you are using a standard no-clean flux you may therefore experience increased bridging on the circuit board.
The question whether to use a VOC-free flux does not only depend on whether the soldering process is being changed to lead-free. Central issue in this context is usually the matter of environmental compatibility. General recommendation for a completely lead-free, solvent-free and “environmentally friendly” process is the use of VOC-free fluxing agents. Practical experience shows that these fluxing agents provide soldering results almost as good as the no-clean fluxes on alcohol basis. Preheating, however, has to be adjusted to the greater specific heat of evaporation. Spray fluxer material compatibility has to be looked into, too. Some of the VOC-free fluxing agents show a very low pH value and have an extremely corrosive character. If the materials used are not stable, the likeliness that the fluxing area of the soldering system will be damaged by corrosion in a very short time is very high.

2.2 Preheating

Preheating rates highly in lead-free soldering. This is due to the very small difference in temperature between melting point and solder bath. A maximum solder bath temperature of 260°C was prescribed for the real-life test. Many SMD component data sheets indicate his limit temperature for wave soldering and in-company QA provisions of the user in question did therefore not allow a higher temperature.
This means that the SnCu0,7 alloy has to be processed at merely 33 K above its melting point, the SnAg3,8Cu0,7 alloy at no more than 43 K above m.p.. At a processing temperature of just 250°C, the temperature difference in case of SnPb increases to advantageous 67K.

This is why preheating has to be precision-adjusted to component, solder and flux. The need of individual reactions can be fulfilled only by a flexible, highly reactive preheating system. Plus the fact that smaller components must not be overheated and larger ones must have reached their required heat at end of the preheating section. The best way to satisfy all these requirements is the employment of a preheater combination. Here primary heating is taken care of by a medium-wave IR emitter. The flexible component could be realized with a short-wave quartz lamps. Convection heaters make sure that massive components are securely but not overly heated. The convection heaters form the end of the preheating section. This combination of various heating systems has shown its practical worth in case of mixed products.
If VOC-free fluxing agents are used, the higher specific heat of evaporation of water against alcohol has to be taken into account. Higher heat of evaporation means higher consumption of energy. For the preheating section of a wave soldering system, a plus in energy not necessarily requires higher temperatures. Different practical tests have shown that a certain amount of convection is most effective in preheating.

2.3 Soldering Module

Specialized literature often recommends setting the soldering temperature for lead-free wave soldering to at least 285°C because lower temperatures would not allow a secure process. Unfortunately, such recommendations do not mention the marginal conditions they apply to. The three-year real-life test has shown that it is very well possible to work with low solder bath temperatures. As described in section 2.2, a temperature of 260°C is the upper admissible limit. In case of the SnAg3,8Cu0,7 alloy, a working temperature of 255°C proved to be absolutely sufficient for the PCBs described in section 2.4.
Modifications have to be carried out at the solder unit in order to satisfy the high-quality requirements on the soldering joints of lead-free solders.

2.3.1 Choice of Material

The recommended, highly tin-bearing solders are very aggressive and attack metals stronger than the well-known SnPb solder. After a very short time, the for soldering nozzles commonly used 1.4301 material starts to show small areas in which the solder wets the stainless steel. Once started, wetting is hard to be stopped and the wetted spots keep growing. After some six months the stainless steel sheet has usually dissolved so much that holes start to form (see figure 1). The reason for the dissolution is the high share of iron in stainless steel. Tin and iron bond to form, for example, $FeSn_2$, i.e. the iron contained in stainless steel goes into solution and destroys the machine components.

Alternative materials that are resistant to the wetting of the solder are available yet hard to work and most often very expensive. Ceramics or casting materials, for example, require moulds that do not allow short-term modifications on the solder pot or solder nozzles. Titanium as material for solder pot, solder pump or nozzles is expensive and requires a high amount of experience during processing. Furthermore, titanium also reacts negatively to tin wetting; although it takes titanium a bit longer to go into solution, the machine components will nevertheless be damaged by pitting.

One further possibility of protection is the surface coating with non-wettable layers. We have the choice among various systems that strongly differ in cost and application. Protective ceramic coatings or enamel surfaces prove to be long-term resistant to tin and offer the best protection in time.

The disadvantages of these coating systems are, however, frequently very serious. Ceramic coating techniques such as flame spraying, for example, do not reach hidden areas and undercuttings. For this reason, the technique cannot be used for the coating of solder nozzles, pump housings and pump channels. Procedures such as the CVD technique have no such disadvantages. They are, however, very high-priced as the process is carried out under vacuum conditions and the large components require large recipients.

Enamel layers have an uneven surface structure and are therefore not suitable for sealing surfaces as between pump channel and solder nozzle. Sharp edges and bore holes are just as hard to protect as in such places enamel tends to retract due to the surface tension. The remaining thin enamel film is very fragile and likely to peel off.
The changes in temperature around the solder pot may also have a negative effect on the adhesivity of the coatings. Around such areas, different CTEs of basic material and coating may cause cracks and partial unbonding of the layers. Especially during the heating up of a solder pot the heating area, due to the higher energy density, may experience higher temperatures than during normal operation.

All these layers are prone to surface damages caused during normal day-to-day production, maintenance works and/or cleaning. Surface damages cannot be repaired on site by the user himself. These spots therefore involve the risk that sooner or later the basic material will be attacked and weakened.
Simple alternative are the temperature-resistant topcoats. As their adhesivity is not as strong as that of ceramics or enamel, all damaged spots around the solder pot and nozzle can be easily reworked and repaired on site by the user. This is particularly recommendable when, for a certain period of time, older wave soldering systems need to operate with lead-free solders.

Modern wave soldering systems allow the use of lead-free solders. Any wetting of the basic material and subsequent damage of machine components is prevented by using special high-quality steels with special multi-level surface treatment. In theory, the surface is absolutely inert to tin. In practice, this claim has been confirmed for machines that have been functioning in normal atmosphere and two-shift operation for several years. Figure 4 shows a main soldering nozzle in use for three and a half years in a SnAgCu solder bath and showing no damages. However, it is difficult to give any reliable information on the long-term behaviour as it is impossible to accelerate and so simulate either aging process or wear and tear, and there are not yet any practical values from the manufacturing industry.

2.4 Soldering Quality

First lab tests have shown that the flow characteristics of the highly tin-bearing alloys cannot be compared to those of SnPb. This led to the modification of the nozzle geometry in order to adjust the board peel-off from the soldering wave to well-tried parameters. The new soldering nozzle geometry guarantees a very good peel-off and the process window ensures a solder defect rate to the user that is comparable to the preceding SnPb process. The PCBs are mixed telecommunication boards for broad-band cable networks in multilayer technology with a maximum of 8 layers Cu and a thickness of 1.6 mm. The smallest So IC contact spacing is 0.7 mm. Figure 5 shows an immaculately soldered QFP with a 0.8 mm pitch.
The solder temperature increase to over 260°C for the improvement of the wetting characteristics, has to be checked very attentively for each single case as the higher temperature load may damage the SMD components and cause PCB delaminations.

As in the SnPb process, the use of nitrogen as protective gas atmosphere offers advantages as the process window enlarges and the dross formation on the expensive solder become less. The here described pilot project, however, was carried out on a wave soldering system without inert gas protection in order to develop a secure lead-free soldering process for the many users of conventional wave soldering systems, and to gain experience in this area.

A very critical item regarding the long-term behaviour of the solder alloy is the stability of its composition. Eight weeks of production have been enough to make some specific alloy components exceed the tolerance range. The copper element dissolves very quickly and accumulates in the solder pot. The closer the Cu contents get to the saturation limit, the more intermetallic Cu_6Sn_5 needles develop. These needles affect the flow characteristics of the solder enormously and cause increased bridging and icicles. At high concentrations, the needles are detectable on the soldering joints themselves (figure 6). A stable process can therefore be guaranteed only if the solder baths are analysed at regular intervals. If the high costs prevent the solder from being replaced it might become necessary to readjust the alloy from time to time by means of an exact calculation and addition of the necessary ingredients. The random addition of basic alloy solder ingots is not possible over a long time.

Not to forget a small but important detail: the solder level sensors in the solder baths that function according to the floater principle do not work in the lead-free alloys. The floaters are usually made of stainless steel, i.e. their density is higher than that of the solder and the floater body “drowns”.

3. Prospects

The change to lead-free solders has become autonomous for many reasons, one of them the aggressive marketing strategies of Japanese companies. It is ruled by the market and finalized by our legislation and the course is set. The consumer industry will be among the first to notice the effect of this change, and most likely long before 1 July 2006, the date fixed by the EU for the final restriction of hazardous substances (ROS 2002/95/EC). It will not only affect the producers of electronic systems but all those involved in the production process up to the equipment manufacturers. The fact that there is no SnPb drop-in solution is going to force the manufacturers to adapt to and deal with new solder materials.

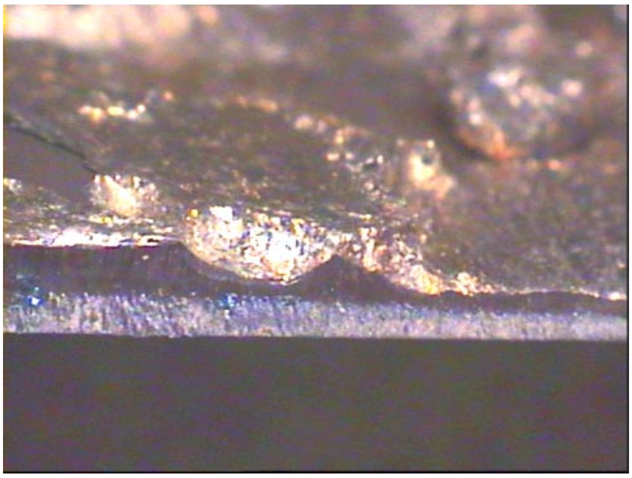
A long list of basic examinations will be necessary to nevertheless provide secure processes for reliable solder joints with long life cycles. Top item on this list is the effect of high temperatures on component and PCB. Another one the influence of different component and pad metallizations. A 24-hour soldering lab test cannot answer the question of series production capability. We need reliability tests on a broad basis to guarantee secure processes. Not to forget the fact that today's specifications and standards base on long years of experience with SnPb solders and will have to be adjusted to lead-free solders. The necessary test jobs are carried out in different study groups and individual companies and there are already a large number of test results available.

Existing products that cannot be redesigned raise the question for their possible replacements or transformations to lead-free use and the answer will have to take all module conditions into close consideration.

The alloy should be chosen according to its worldwide availability and international trends and recommendations. Exotic solutions soon hit dead ends.

Pic. 1: Defective Pump Housing

Pic. 2: Dissolved Area / Detail



Pic. 3: Cut through solder nozzle wall section

Pic. 4: Solder nozzle from modified material after 3,5 years of use

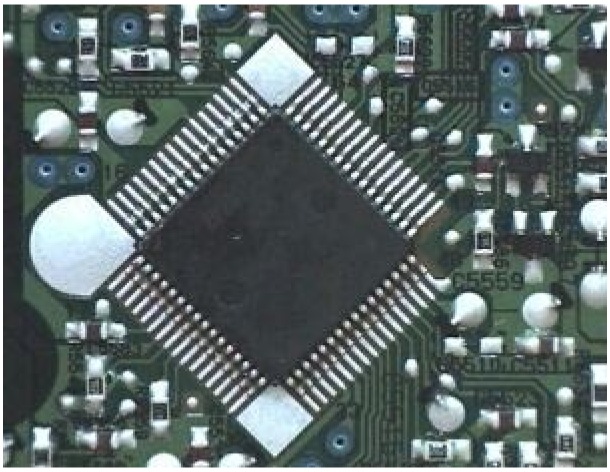


Abb. 5: QFP 64 wave soldered, pitch 0,8 mm

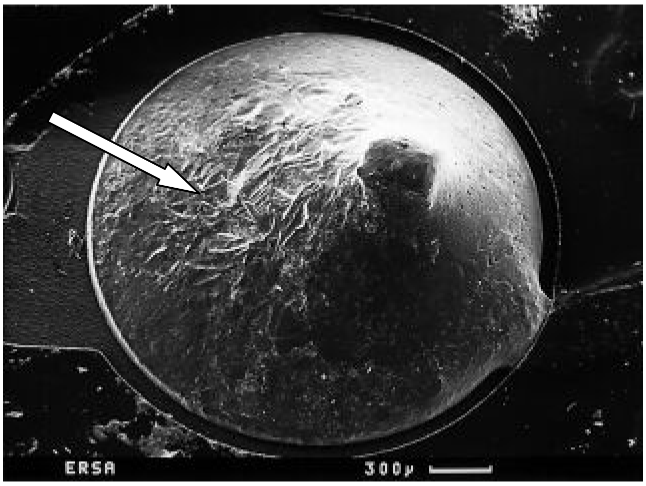


Abb. 6: Needles of Cu_6Sn_5 in a soldered joint