The Lead-Free Wave Solder Process and Its Effect on Laminates

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Abstract
The pressure on manufacturers of electronic devices to continually reduce the cost of products has continued, despite the challenges of higher cost lead-free production. In many cases assemblers have been forced to attempt to build the new lead-free assemblies using the same equipment, and without increasing the cost of components and laminates. While many manufacturers have considered reliability data from materials suppliers and independent test houses, many have not considered the reliability impact on their own particular assemblies. This paper discusses the potential effect on the reliability of a lead-free assembly in relation to the laminate used and the process parameters.

Introduction
The transition to lead free soldering has become a reality for electronics assemblers in many sectors. In many cases process parameters have been adjusted to improve upon in-process yields, since the initial alloy selection investigations from several years ago. In addition, many assemblers have moved to newer flux chemistries in order to cope with the process challenges posed by the selection of alloy options which all have slower wetting speed, higher surface tension and higher processing temperatures when compared to tin-lead.

Whilst assemblers have had to deal with these process challenges, the market for low cost consumer goods has experienced a rapid deflation of high street prices for most audio-visual products. Lower cost manufacturing centres and new brands have increased the price pressure on the established brands.

Wave soldering is a very key process for the production of many consumer electronics, and the switch to lead free production has several cost implications. In broad terms the costs fall into the categories of (i) PCB and components cost (ii) soldering materials and consumables cost (iii) processing costs .

As consumer electronics manufacturers have had to accept higher materials cost and higher process costs in switching to lead-free, they have been forced to avoid other cost increases such as the use of more expensive, more thermally stable laminates. What has not been assessed in many cases is the impact of those process changes on the reliability of the product in terms of mean time to failure in the field. This paper aims to expose the potential impact of assembly materials and processes on the in-service reliability of circuits.

Challenges of the Lead-Free Wave Soldering Process
Alloy Selection and Evaluation
If we observe how alloys were selected, the evaluation was typically done in three stages. The first evaluation criteria are deemed to process performance indicators. They are not direct measurements of the wave solder processes but measures of the alloys key characteristics that are known to impact the in-process performance. The actual performance of the alloy is then assessed in a controlled wave solder process in order to assess its effect on process yield. The final stage is the testing of the solder alloys for in service reliability using mechanical testing and accelerated aging by thermal cycling. The final stage is often used as a benchmark of solder joint integrity and reliability of the candidates, with relation to the baseline of tin-lead. What is often lacking in many studies is the impact on components and PWB's from extended thermal processes imposed by lead-free alloys.

Process Yield
All production professionals know that the cost of materials has little influence in comparison to their effect on process yield. A step change in process yield could have very dire consequences on the profitability of a production line, especially for the contract electronics manufacturer (CEM).
The number of soldering defects created in wave soldering is intrinsically linked to the flux, alloy, alloy purity, PCB/component finish, PCB layout, and atmosphere and process settings. In moving to lead-free wave soldering we are moving towards a reduced process window, and therefore the key task for process engineers is to widen the process window enough to achieve acceptable results (outputs), whilst minimizing the cost impact on the process (inputs).

As already discussed, some key characteristics of an alloy have very significant effects on wave soldering results. Slower wetting and lower fluidity can translate into an increase in unsoldered or partially wetted joints. An unsoldered joint may not be detected at In-Circuit Test (ICT) or at functional verification testing (FVT) as electrical contact between the termination and the PCB pad will be intermittently possible. Solder bridges that cause permanent effects on circuit functionality are easy to detect by manual and automatic inspection methods. Increased bridging has been seen in most lead-free installations and is caused primarily by the alloys higher surface tension and therefore poorer drainage from the solder joint. The natural process remedy for the increase in bridging is to increase the process temperatures, both pre-heat and solderpot, which can have a deleterious effect on the laminate and components

Process Performance of Lead Free Alloys and their Impact on Process Settings
Solidus/Liquidus Temperatures.
All of the common lead-free alloys have a higher melting point than tin-lead. As a result of this, operating temperatures need to be higher for successful processing to allow adequate fluidity and drainage of the alloy. The process window between alloy liquidus and acceptable operating temperature for lead-free alloys is about 60% of the window allowed for tin-lead processing, as can be seen in figure 1 below.

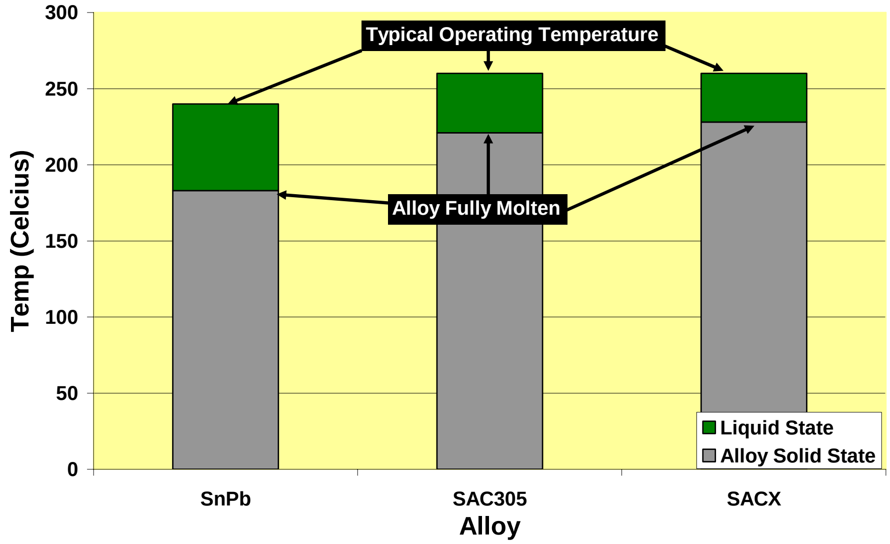


Figure 1 – Alloy Operating Window

Exploring what impact alloy temperature has on performance gives some indication of the challenge to the process engineer. Table 1 shows the generic performance responses to alloy temperature variation.

Table 1 – Effect of Alloy Temperature on Defects

	Temperature Lower	*Temperature Higher*
Drossing	*Better*	*Worse*
Bridging	*Worse*	*Better*
Hole Fill	*Worse*	*Better*
Unsoldered Joints	*Worse*	*Better*
Laminate Damage	*Better*	*Worse*
Component Damage	*Better*	*Worse*

Most evaluations are primarily focused on the first four performance metrics in the list. The reason for this is simple: they are quantifiable attributes that can be measured *during* a trial. As it is process engineers who typically have responsibility for designing and implementing efficient and high yielding processes, there is a great tendency to lean towards higher operating temperatures as a means to improving yield.

Wetting Speed Defines Contact Time

It is not just alloy temperature which impacts process performance of an alloy. The wetting speed of alloys can be quantifiably compared using a wetting balance. The wetting balance test is classified in ANSI/J-STD-002 as a "Test without established Accept/Reject Criterion." These wetting balance tests have been used in the past to measure the solderability of components and as an aid to developing and testing fluxes. However if test variables (sample, flux, temperature) are kept constant then this can be used as a relative measure of the alloy performance. A faster wetting speed will enable reduced solder contact time and hence faster throughput. In addition to faster throughput a shorter contact time also has the benefit of less thermal exposure to both the laminate and components.

The following aspects of the process of wetting are very important:

- Melting temperature of alloy
- Flux chemistry –activation, temperature effects
- Wetting and surface tension properties of the alloy

In many alloy evaluations, there was no link considered between the wetting speed of an alloy system and the impact on reliability of the assembled circuit. But the reality is that the wetting speed of the alloy will largely affect the machine settings, which in turn affect the amount of heat energy which the assembly will see, which in turn can have a detrimental effect on reliability. Consider that within the wave soldering process, the solder needs to find its way into a vast array of dimensions and geometries, and then wet to the solderable surface. Failure to do both of these is often caused by insufficient contact time with the assembly. The net result of insufficient contact time is a rise in skips (unsoldered joints), and reduced hole-fill for PTH boards.

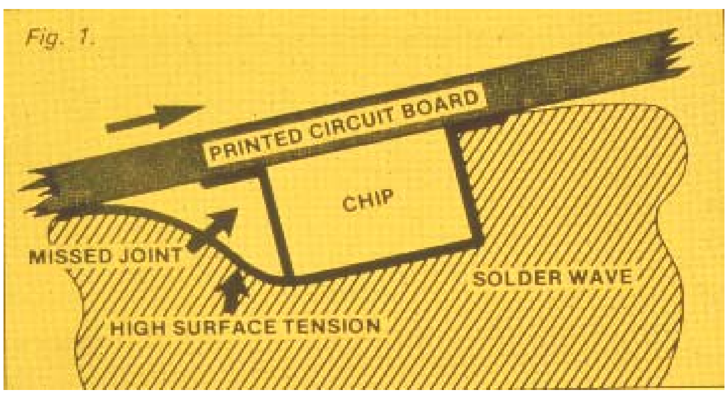


Figure 2 – Effect of Surface Tension on Solder Skips

Let us consider figure 2, an illustration taken from an old text. The lead-free alloy has a higher surface tension than tin-lead and so relies even more on kinetic energy from the wave to get the molten solder in contact with all surfaces to be soldered, only then do we reach T_{zero} on the wetting balance chart. If the relative wetting speed of three alloys is as in the wetting balance chart shown in figure 3, then Alloy A may form solder joints where B and C skip.

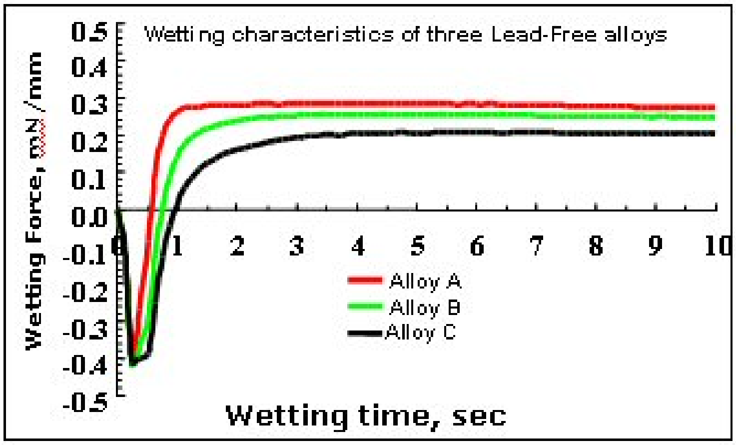


Figure 3 – Effect of Alloy Choice on Wetting Speed

Tin-lead alloy consistently shows faster time to buoyancy, or wetting on a wetting balance. It is not surprising then that many engineers found an increase in skips when initial lead-free pre-production trials where conducted. The result of this was the need to substantially increase contact time on the wave by a slowing of the conveyor. For a dual wave system the contact time is measured by adding the contact width of the chip wave (CW) and that of the main wave (MW) and divide by the conveyor speed. Figure 4 shows a typical dual wave configuration.

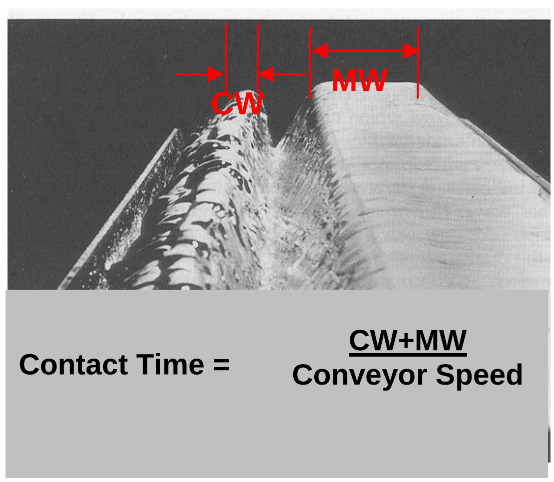


Figure 4: Dual Wave Configuration

It can be seen from the table 2 the engineer will find more reasons to slow the conveyor in order to achieve an acceptable process yield. This allied with a higher pot temperature has a very significant impact on the thermal excursion of the printed circuit assembly and needs to be considered further as part of the overall reliability of the lead-free assembly.

Table 2 – Effect of Contact Time On Yield

	Conveyor Slower	Conveyor Faster
Throughput	Worse	Better
Hole Fill	Better	Worse
Unsoldered Joints	Better	Worse
Laminate Damage	Worse	Better
Component Damage	Worse	Better

These limitations of alloy performance have driven engineers down several routes to mitigate the need for excessive temperatures and contact times. The 3 broad areas to consider are the following:

(i) Soldering atmosphere
(ii) Flux Selection
(iii) PCB design

(i) : Soldering Atmosphere – Nitrogen

Often the reasons cited for the inclusion of a nitrogen atmosphere in wave soldering is a purely economic argument, based on the savings from a reduction in dross production. It is interesting to note that this is not the only positive impact and that for lead-free production; it could be the difference between achieving both a high yielding process and a high reliability end product, and finding a process compromise between the two.

The inclusion of nitrogen or more precisely the exclusion of oxygen in a soldering process has a number of advantageous response variables. The first is the increase in wetting speed. If we fix the solder temperature, the flux and the solderable coupon, and then run a wetting balance test in air, then repeat in nitrogen we see a considerable wetting speed advantage in nitrogen. If we then run a wetting balance test with variation in solder temperature and repeat for air and nitrogen, we will see that wetting speed is also governed by the solder temperature. The response can be seen in figure 5.

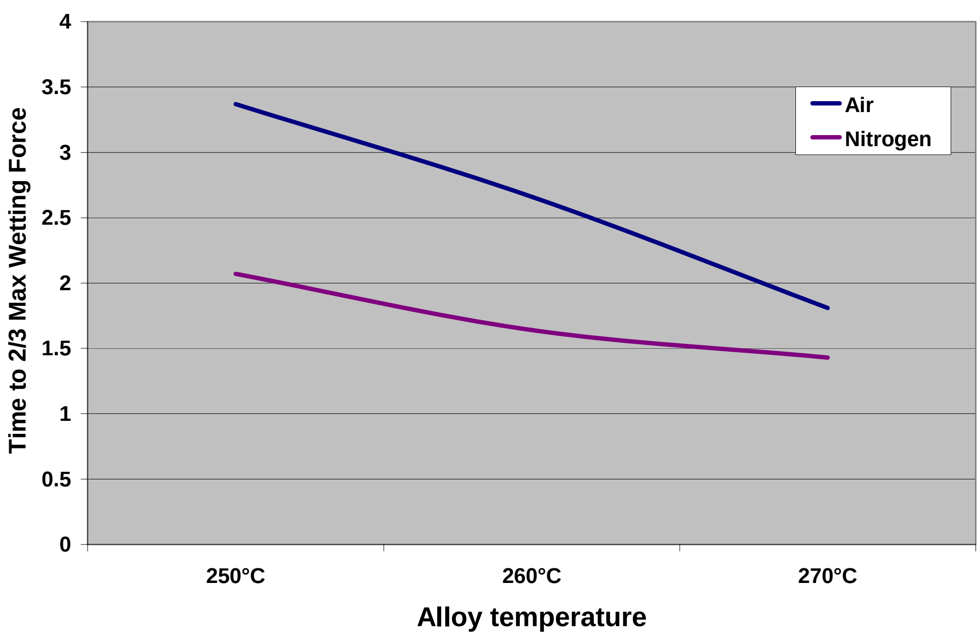
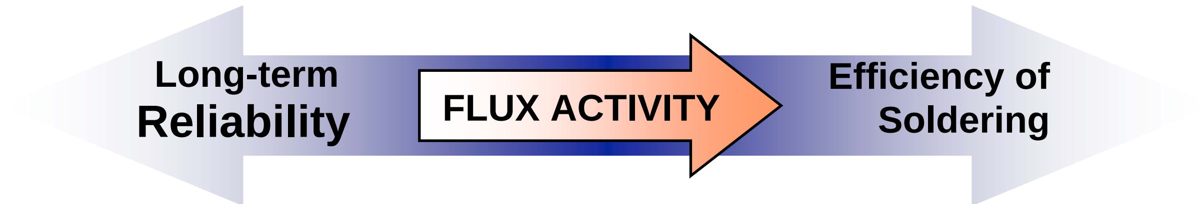


Figure 5 - Impact of Temperature and Atmosphere on Wetting Speed

As can be predicted from the above, inert atmosphere wave soldering gives the option to achieve the same or better results with a lower solder alloy temperature, giving less thermal stress to the PCB and components. Possibly a more beneficial impact of nitrogen is the option to reduce contact time because of the faster wetting characteristics: this both improves throughput and moreover, reduces the thermal stress on the PCB caused by dwell time on the wave. These benefits are further enhanced by the reduced creation of dross.

(ii): Flux Selection
There is a delicate balance to be struck with selection of fluxes. At one extreme is the selection of a flux so weak as to not give any risk of post soldering corrosion. This can inadvertently lead the process engineer to more extreme process settings to achieve acceptable soldering results and also cause a lot of rework, which in itself will negatively impact reliability. At the other end of the spectrum is the use of a flux so aggressive, that reliable soldering is achieved at the expense of electrochemical reliability of the flux residue. It is this balance which must be struck for each application and which has made wave solder flux selection a critical activity.



For FR-2 laminates it is worth noting that rosin-free fluxes can cause a reliability risk if not heated sufficiently. FR-2 acts like a sponge and any unused activator can be free to form an electrolyte in water if the end product is operated in a damp environment. On the other and, the use of rosin acts as an encapsulant for other active ingredients in the flux, leaving a safe residue on the PCB. Rosin is dissolved into the carrier solvent, along with other active materials during flux manufacture. During the soldering process it becomes molten and acts as a thermally stable aid to the soldering process, and when cooled it solidifies to act as a hydrophobic encapsulant to any ingredients which may not have volatilized during the soldering cycle. This encapsulating action allows formulators to produce relatively aggressive fluxes for high soldering yields, whilst not compromising on post soldering reliability.

(iii) : PCB Design
The capability of any wave soldering process is a function of machine, materials, process settings and of course PCB design. As the process window narrows, inevitably the process inputs all become more critical. On the subject of PCB design it is more critical to have component orientation such that all areas to be soldered have an equal exposure to the wave. This is especially important for high bodied components who can suffer from shadowed skips if not placed optimally.

Pad sizes and geometries should also be considered carefully. Failure to consider pad design can negatively impact the reliability of the product by forcing the process engineer to use excessive pot temperature and contact times to achieve adequate wetting. This is especially important for the FR-2 which is less thermally and dimensionally stable than for expensive epoxy glass systems. The following illustration shows the positive impact of extending pads of components to help the lead free alloy to start the wetting process earlier.

In Service Reliability
The in service reliability of lead-free alloys and lead-free solder joints is relatively well known. The impact of process settings variations on the reliability of the complete assembly is less well understood. This is a great concern for OEM's anxious to retain good reputations for quality and reliability, especially when process control is in the hands of a third party such as a CEM.

Accelerated life testing uses different profiles depending on the end use of the PCB. They range from 0 to 80°C, which is acceptable for some consumer electronics to -40 to 165°C that may be an aspiration for electronics in a harsh environment such as under-hood automotive applications. For the case of products built on FR-2 laminate, the biggest concern is due to the poor planar and dimensional stability of the laminate placing enormous stress on the solder joints. Whilst many of the through hole solder joints are relatively large in dimension, the lack of a plated barrel means the joint is less mechanically and electrically robust than an equivalent component in a PTH scenario. Thus a number of inspection standards have been developed to visually assess the solder joints on single sided FR-2 PCBs such as the example below…

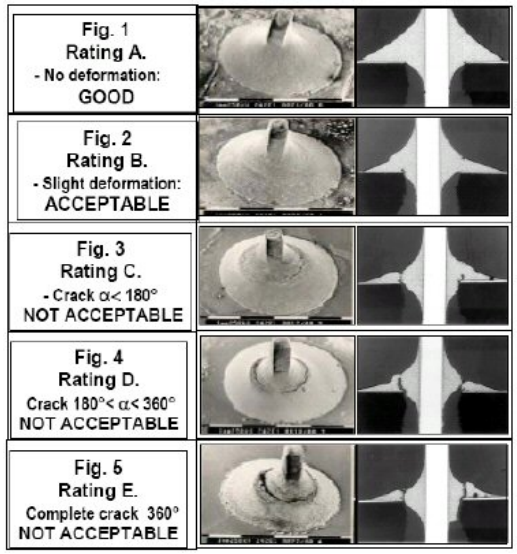


Figure 6 - Visual criteria for acceptable Joints (Courtesy of Philips)

The concern over the in-service reliability of FR-2 assemblies is shown by the rating E above. This can give rise to intermittent failures during the typical end-use of the product. As the product increases in temperature after switch-on, expansion and warping of the laminate causes the crack in the bulk solder to open and in doing so, causes the product to fail. Once the product has cooled down it will often work again, for a short period. An example of this failure mechanism is shown in the photographs in Figure 7,

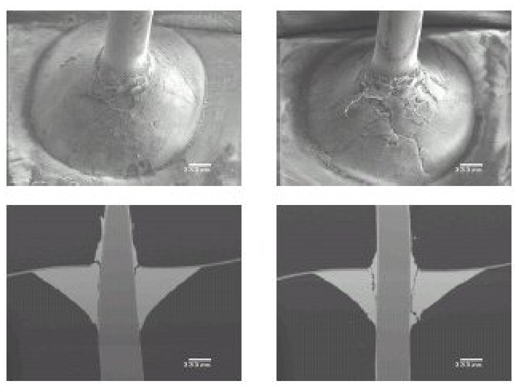


Figure 7 - Single Sided PCB Through-Hole Joint Failure

The performance of a solder joint subject to thermal stress is dependent on the physical properties of the solder alloy and the joint formation. Therefore a poorly formed joint will deteriorate to failure more quickly than a well formed joint. The stresses induced during thermal cycling and in day to day operation can be large enough to produce microstructural changes in the solder joint, including the nucleation of fatigue cracks and joint failure. This is a progressive mechanism; once a crack has nucleated it may proceed to grow. The fatigue crack mechanism is as follows:

• Stress creates delineation of individual grains and porosity.
• Delineation is caused by a breakdown of inter-granular cohesion, grain deformation effects or micro-structural coarsening effects or a combination of these factors.
• A fatigue crack is caused by the coalescence of voids or during grain boundary separation of highly stressed regions.

In consumer electronics the combination of excessive processing conditions followed by the stress induced by daily switch-on/switch-off cycles, has given rise to significant concern over the lifetime reliability performance of many domestic products.

Conclusion

The reliability of end-users product is affected not only by material & component selection and design & workmanship standards, but it is also very much linked to the assembly process parameters. The need to appreciate that some methods for improving process yield may detrimentally affect product reliability is greater than ever and with the challenging lead-free processes of today. Process settings need to be optimised and then enforced to avoid the effects of "night shift tweaks" – those small parameter adjustments innocently made to avoid minor process defects.

While the lead-free transition has been a challenge, it has forced the electronics manufacturing community all to understand the intricacies of the assembly processes better than ever before. The considerations of failure mechanisms should also be understood, and risk assessments made for all product groups in order to avoid unexpected warranty claims.