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Selective Soldering with Alternative Lead-Free Alloys

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Abstract

The electronics industry is still searching for alternative lead-free alloys. Selective soldering requires relatively high solder temperatures to get proper hole filling. Alternative alloys with lower melting temperatures may wet faster and open the process window. These low temperature solders (LTS) are of interest in SMT soldering because of reduced warpage and voiding risks. The question is how these alloys respond in liquid soldering applications. Lower operating temperatures reduce the risk of damaging plastic parts or secondary reflow on mixed technology boards. The preheat temperatures are close to the melting point of the alloy which will make the solder flow easily to the solder destination side of the board. Fluidity of these alloys may change at higher temperatures and it will be interesting to see the impact of the melting range on solidification of the solder.

Other alloys are designed to be compatible with extreme thermal exposure in operating environments such as under-hood automotive, avionics/aerospace and other severe operating environments. Their wetting properties are important to get hole fill at reasonable solder temperatures. This study investigates new alloys and their properties in lead-free selective soldering applications. Does their fluidity influence the wave stability on wettable and non-wettable nozzles? The impact of the solder temperature on hole fill and bridging is tested. A test-board with fine pitch components from 1.00 mm to 2.54 mm pitch is used to define the bridging risk.

There are new technologies on the market that make it possible to design very odd-shaped nozzles. De-bridging can be much more efficient with this second generation of non-wettable nozzles in combination with advanced nitrogen-gas nozzles to eliminate bridges. This patented nozzle technology will be compared to the conventional nozzles.

Introduction point-to-point soldering

In a selective soldering point-to-point process THT (through hole technology) components are soldered with a small solder nozzle. This can be done by dipping or dragging the component through the liquidous solder. Although this process is very consistent and reliable there is some noise that reduces the process window:

1. Boards are twisted due to prior heating processes like reflow soldering.
2. Board finishes are hard to wet due to previous heating cycles (oxidation of metal) like reflow soldering.
3. SnAgCu lead-free alloy requires high process temperatures to achieve acceptable hole filling.
4. Wettable nozzles may oxidize (de-wetting) and require monitoring to avoid defects.
5. Flux needs high activation and must be compatible with high solder temperatures. There is a potential risk for electro-migration if the flux is not completely activated.
6. There is a potential risk for bridging when soldering fine pitch components.
7. Cycle time might be an issue for some applications.

This paper discusses technical solutions to open the process window.

Prior to selective soldering, the board is reflowed one or multiple times. Most boards will twist because of these multiple heating processes. This warpage is noise in the selective soldering process. Using low temperature solders in the SMD process will benefit the selective soldering process. SnBi based alloys have low melting points that allow reflow soldering with peak temperatures of 200-220°C. This will depend on the thermal mass of the board and the components. A typical superheat
(peak temperature – liquidus temperature) is 15-25°C. Based on this the LTS alloy must have a melting point below 200°C. Lower peak temperatures mean that less expensive substrate and component packaging materials can be used instead of more expensive alternatives. The mix of materials, with a wide range of coefficients of thermal expansion (CTE), thermal mass, and thermal conductivity, used in the construction of complex area array packages mean that when exposed to a typical lead-free thermal profile they warp to an extent that make it difficult to assure the integrity of all the joints of the component [1]. Board materials with lower glass transition (Tg) temperatures can be used since base material will remain stable at such low

reflow temperatures. Multiple advantages when reflow temperatures are lower including less voiding. It may also be possible for some THT components to be replaced with an SMD alternative.

Warpage compensation

A multilayer test-board was designed to define methods to process twisted boards. This test-board had different patterns on it with multiple Cu-layers. The board has a high thermal mass on one side and low on the other. There is no symmetry so there will be significant warpage after reflow soldering.

Figure 1 - The multi-layer test board with test points.

A laser sensor measures the twist of the board on the nine red marked points. The solder pot is mounted on a robot. The software can correct the solder pot height. Before Z-height compensation the height difference can be up to 1.5 mm. After compensation it is less than 0.5 mm.

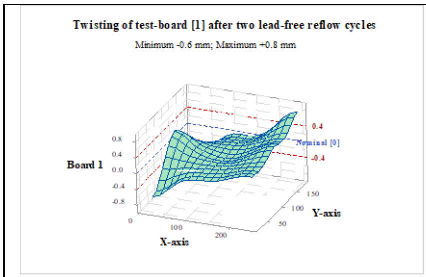
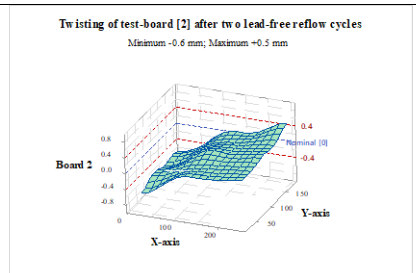
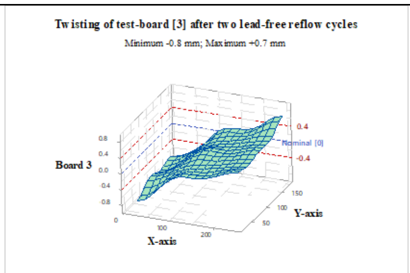
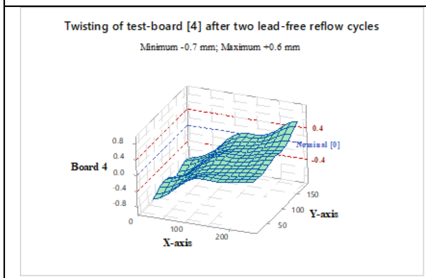
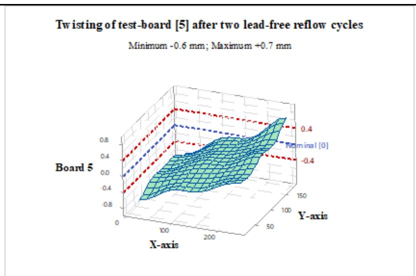
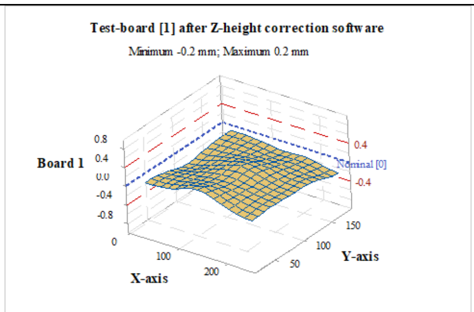
		
Board 1: minimum -0.6 mm maximum +0.8 mm	Board 2: minimum -0.6 mm maximum +0.5 mm	Board 3: minimum -0.8 mm maximum +0.7 mm
		
Board 4: minimum -0.7 mm maximum +0.6 mm	Board 5: minimum -0.6 mm Maximum +0.7 mm	Board 1 modified: minimum -0.2 mm maximum +0.2 mm

Figure 2 - Test-board warpage compensation with board 1 compensated by software.

The warpage of the boards is quite similar. Most likely because of the Cu layers design. If all boards have identical twist the frequency of the measurements can be reduced, and a standard compensation can be applied.

Low temperature solder

The benefits of LTS solder in reflow have been addressed. Lower reflow temperatures result in less twisting and oxidation of the metal surfaces. This opens the process window for selective soldering. In this study LTS solder is used for point-to-point soldering. There are not many elements that have lower melting points than SnAgCu. The SnBi is known for its low eutectic at 138°C and thus a good candidate alloy. The alloy tested is a SnBi based alloy with NiGe addition. NiGe is well known since it is successfully added to SnCu. The excellent reliability properties of the Ni combined with lower dross formation of the Ge will improve the SnBi.

The alloy tested has 28% Bi by weight and a small addition of Ni and Ge. Since the amount of Ni and Ge are less than 1% the SnBi phase diagram can be examined to identify the melting range.

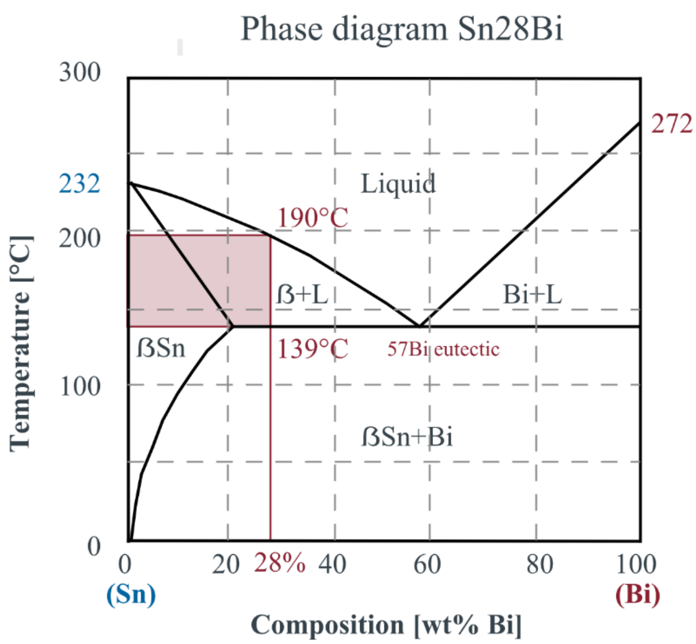


Figure 3 - The low temperature solder SnBiNiGe phase diagram.
The melting range of the alloy is from 139°C to 190°C.

The melting range is confirmed if the temperature of the solder during heating is logged into a file. There is a gradient change in the graph visible at 139°C and another at 190°C. For comparison, the heating of the SnAgCu is drafted in the same graph.

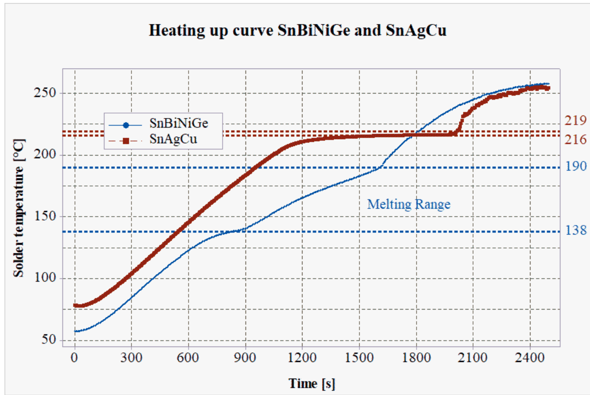


Figure 4 - Heating up the solder results in a slope change at the melting range of the solder.

The SnBiNiGe heats up faster. Its operation temperatures are significantly lower than the SnAgCu alloy. Attention is needed to ensure the pump release temperature is set at a lower temperature. The dross formation is lower not only because of the lower solder temperature, but also because of the presence of Ge.

Wave height stability

For a robust process, a stable wave is a must. The wave height depends on the design of the nozzle and the pump speed. Most point-to-point solder applications use a magnetic pump. The advantage is that there are no moving parts in the pot, which extends the lifetime of the parts. Only the wettable nozzles will wear because of the wettability – intermetallic reaction with lead-free solder.

A typical selective soldering process has boards with a thickness of 1.6 mm. The wave height should ideally be one-half of the board thickness (bottom side board + 0.8 mm). With leads that have a protrusion length of 1.4 mm (typical 3.00 mm – board thickness = 1.4 mm) the wave height should be enough to overcome the warpage of the boards.

There is additional noise – the robot has an accuracy of ± 0.10 mm and the leads may also have tolerance.

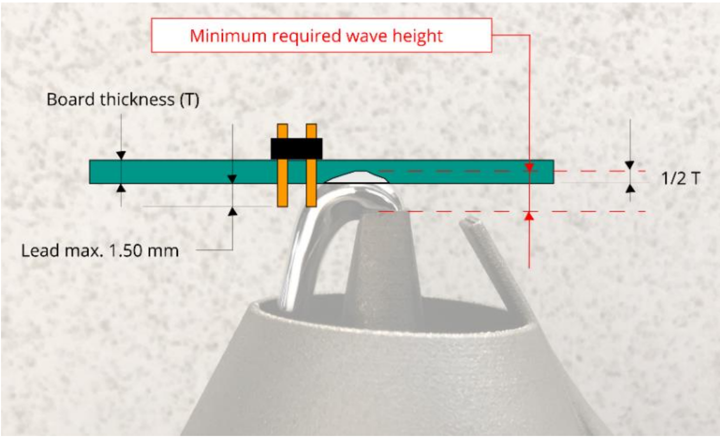
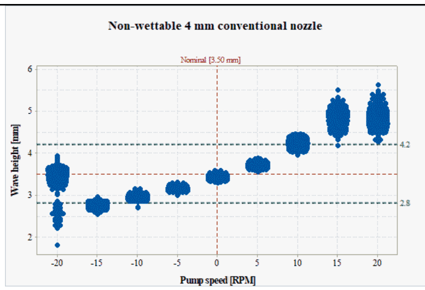


Figure 5 - A typical select wave with minimum height requirements.

Counting all the tolerances together and adding the twisting of the board to it, results in a minimum wave height of 3.2 – 3.5 mm. The stability of the wave was defined ± 0.4 mm for a wave soldering process based on a board thickness of 1.6 mm.

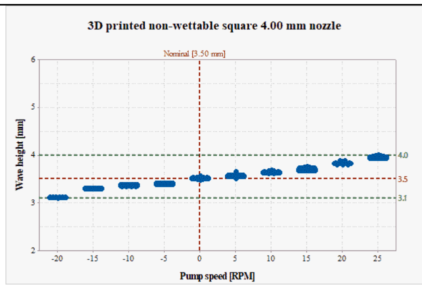
The other factors that may influence the stability of the wave are the solder alloy and the nozzle design. Both parameters are investigated. 3D metal printing offers the possibility to design new non-wettable nozzles out of stainless steel that have shapes with dimensions that never could be made with conventional drilling or machining. These 3D printed nozzles are threated with a diffusion process to make them compatible with the highly erosive lead-free solders.

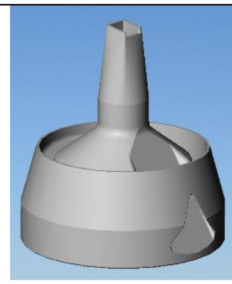
The stability of the wave can be measured with a camera and dedicated software. The results for different nozzles are shown for SnAgCu solder at 300°C. As a reference, the non-wettable 4 mm conventional nozzle is not 3D printed.



Non wettable 4 mm conventional nozzle

Work area 2.80 – 4.20 mm.





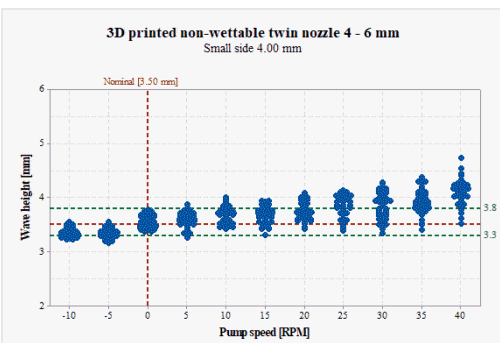
Non wettable 3D printed square 4 mm nozzle

Work area 3.10 – 4.00 mm.

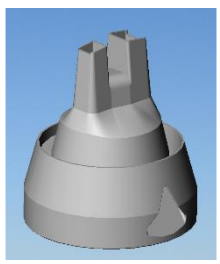
Figure 6 - The difference between a conventional nozzle and the 3D printed square nozzle.

The data shows that the 3D square nozzle is more stable. Changing the RPM's has less impact, so it is easier to make small wave height changes. The wave height range of the nozzle is slightly less but performance overall is better.

A special design nozzle is the 3D printed dual nozzle. This nozzle has a square of 4 mm on the front and 6 mm on the rear side. Since the solder pot has the capability to turn 180° it is feasible to solder both waves without manual interference. One condition is that the board is tilted when soldered. By doing so, one board with different components can be soldered without tooling change which reduces machine interference and downtime.



Non wettable 3D printed dual nozzle 4 – 6 mm.



Both waves have different work areas. The smaller wave 3.3 – 3.8 mm and the wider wave from 2.9 – 4.5 mm.

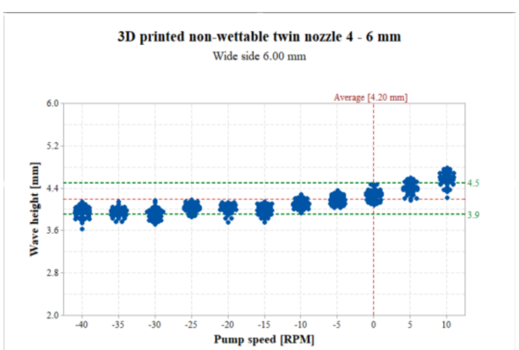


Figure 7 - The dual nozzle has slightly more variation in wave height.

Fine-tuning the holes may result in the same work area for both waves. The wave height not only depends on the nozzle shape but is also affected by the solder temperature.

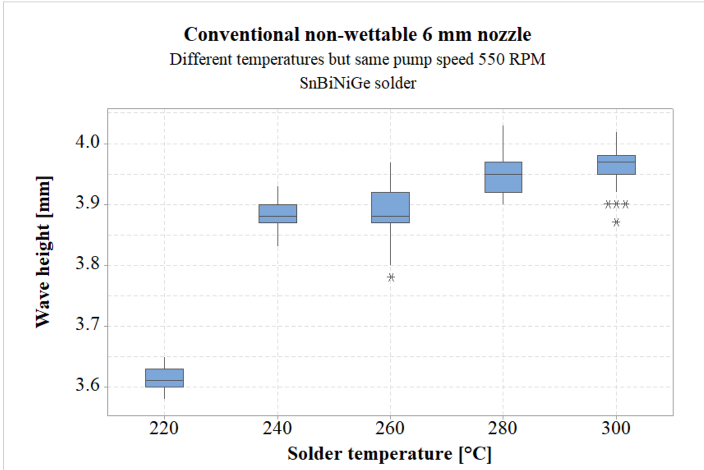


Figure 8 - The influence of the temperature on the wave height for the SnBiNiGe solder.

The wave height changes at different temperatures for two reasons:

1. Fluidity of the solder (viscosity changes)
2. Different coil temperature of the magnetic pump

At a higher solder temperature, the solder will typically have a higher wave because of its fluidity. However, when the coil temperature increases, the wave will become less high. There is an interaction between the two parameters resulting in graph above. At 220°C the SnBiNiGe is very syrupy. The superheat is only 30°C. This would be similar to soldering SnAgCu at 250°C.

Minimum solder temperature for SnBiNiGe

The question is, at what temperatures is it feasible to solder with SnBiNiGe? How much superheat is needed for this solder with a wide pasty range? The first experiments were with a very small superheat. Fine pitch components were soldered at 210 and 230 °C. Cross sections were used to measure the intermetallic thickness of the solder and the Cu barrel and between solder and the lead of the pin header.

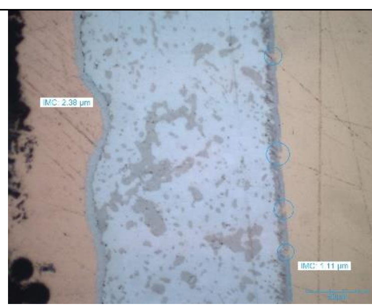
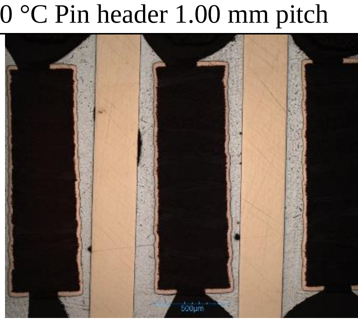
Cross section	Solder and board intermetallic	Solder and pin
		
210 °C Pin header 1.00 mm pitch	Intermetallic thickness barrel: 2.38 µm	Intermetallic thickness: 1.75 µm
		
230 °C Pin header 1.00 mm pitch	Intermetallic thickness barrel: 2.86 µm	Intermetallic thickness: 0.95 µm

Figure 9 - Cross sections of the 1.00 mm pitch connector soldered at low temperatures.

There is some non-wetting visible between pin and solder at 210 °C. For the rest the results are promising. The intermetallic layers are visible and have an acceptable thickness.

A Box-Behnken type of experiment was done to define the impact of solder temperature, drag speed, and pad dimensions on bridging and open joints.
The fine pitch test-board is used with double row pin headers 2.00 mm and 1.27 mm. Additionally, a one row pin connector with 1.50 mm pitch is soldered. The boards are soldered with a 6 mm non-wettable nozzle utilizing a de-bridging tool (Solder Drainage Conditioner). SDC settings: nitrogen flow 6 LPM with a power of 25%. The hot nitrogen is blown just after soldering to remove bridges. For the 1.50 mm single row connector the SDC is off. The design of the experiment is shown in the next graph. The flux used is a no clean REL0 with 2.6% solid and the preheat temperature measured on topside of the board is 110°C.

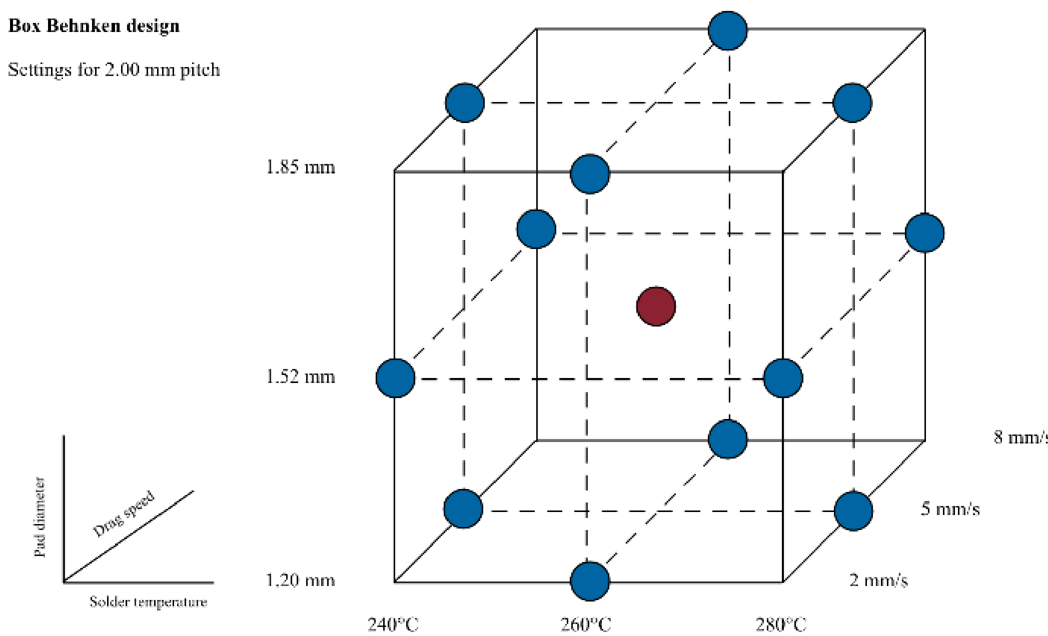


Figure 10 - Box Behnken graph of the experiment with different parameters and set-points. The pad dimensions are the outside diameters for the 2.00 mm connector.

All blue dots are soldered three times and the red center dot conditions are soldered 9 times. The settings for the pad diameter that are listed are for the 2.00 mm pitch connector. For the 1.27 mm the outside pad diameters are 1.00, 1.06, and 1.12 mm. The open joints were counted. Each pin without good hole fill was 1 point so for each connector of 2.00 and 1.27 mm the optimal score was 20. The data was analyzed with statistical software.

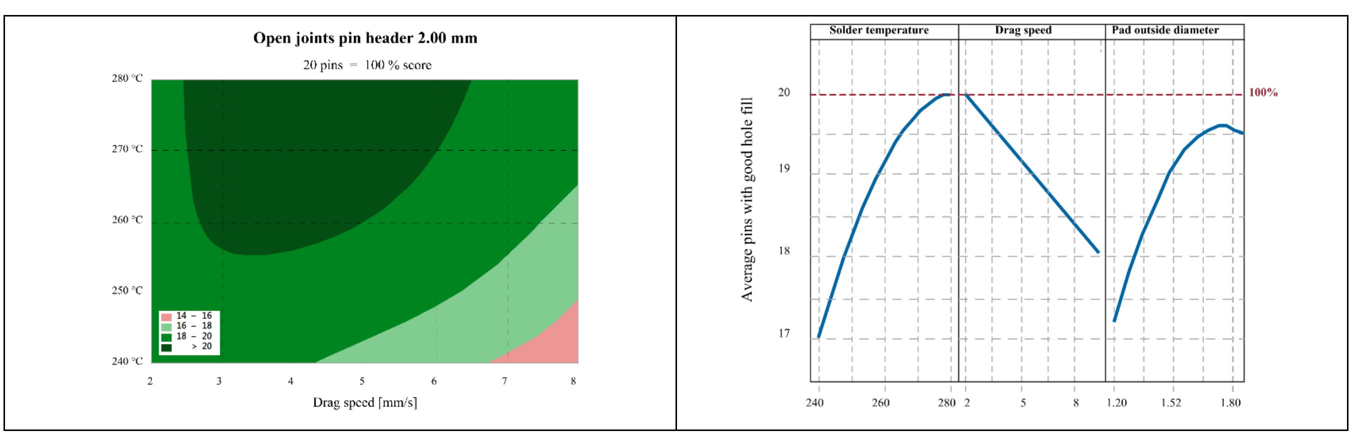


Figure 11 - Open joints were found at higher drag speeds with low solder temperatures.

The highest scores are for 280°C solder temperature, a drag speed of 2 mm/s and an outside pad diameter of approximately 1.70 mm. At a lower solder temperature there are more opens. The lower conveyor speed offers a longer contact time and this benefits the wetting. A wider pad has more metal surface to contact to the solder and therefore wets better.
It was possible to solder with this alloy at 210°C. However, the alloy is less fluid (shown in the wave height measurements) and due to the minor wetting at lower temperatures more opens are found. This is also confirmed in this Box Behnken experiment.

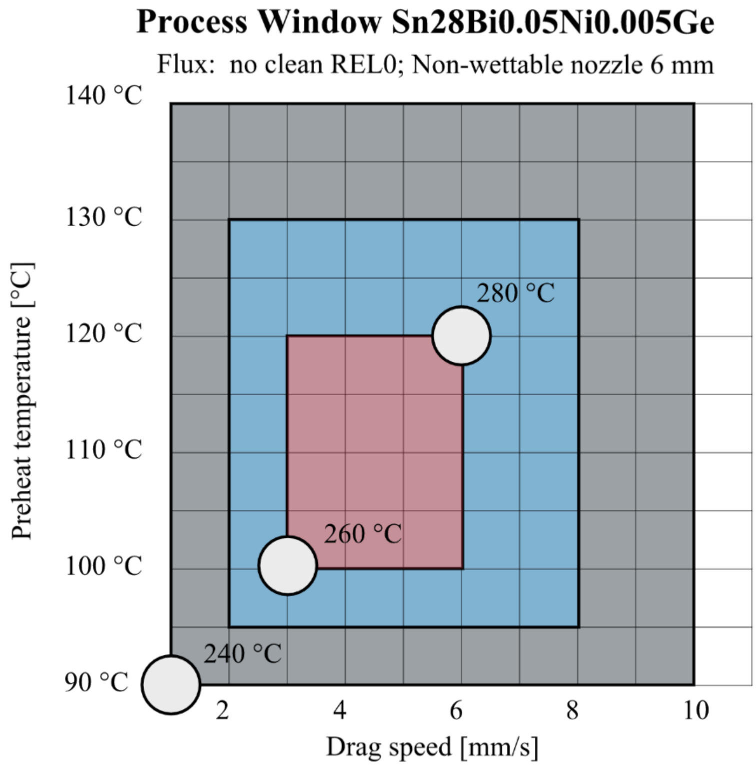


Figure 12 - The work area for this board and flux for the SnBiNiGe.

The work area for the SnBiNiGe based on the fine-pitch test board with this flux. The superheat is >50°C. One of the issues here is the compatibility of the flux with low solder temperature. The traditional fluxes used for SnAgCu may contain activators that are not completely inert after a solder cycle at these low settings. The open joints might be less if an activator is used that responds better at low temperature settings.

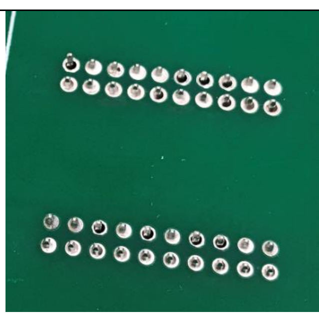
	
Random open joints on header 2.00 mm pitch for SnBiNiGe soldered at 210 °C.	Very nice solder fillet for header 2.00 mm pitch soldered at 240 °C.

Figure 13 - Solder results SnBiNiGe for selective soldering with lower solder temperatures.

Box Behnken experiment with SnAgCu and SnCuBiNiGe

The same experiment is done with two different lead-free alloys on the same machine using the same solder pot and non-wettable nozzle. The alloys are SnAgCu with a small melting range (216-219°C) as shown in the heating curve (Figure 4). The other is SnCu based with the addition of Bi and the NiGe system as in the SnBi low melting alloy. This alloy has a solidus temperature of 221°C and a liquidus temperature of 225°C. The SnAgCu is a standard lead-free solder alloy and is a reference for the other alloys. The SnCuBiNiGe is a high reliability alloy for under the hood applications in automotive industry. The Box Behnken experiment has the same parameters, except the solder temperatures are increased by 40°C. Now the lowest setting is 280°C and the highest solder temperature is 320°C. The superheat for the SnAgCu is >60°C and for the SnCuBiNiGe is >55 °C.

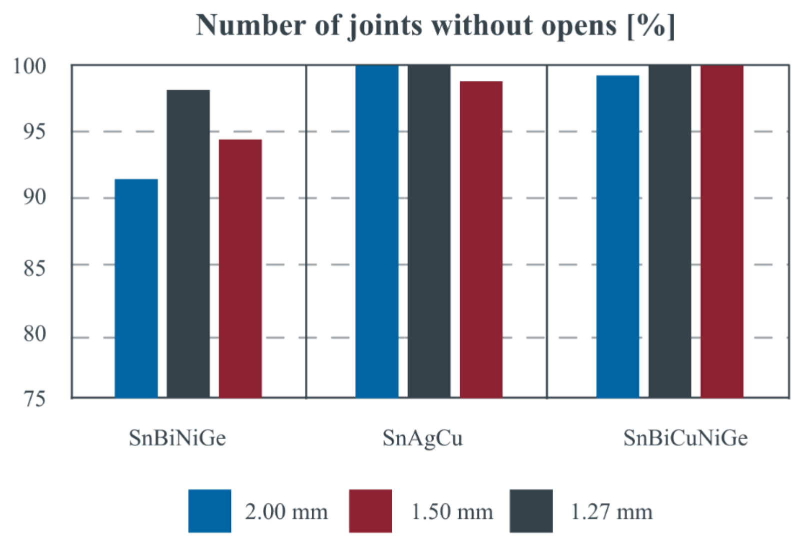


Figure 14 - The open solder joints for the different pitch distances and alloys. The low melting SnBiNiGe had significantly more opens for the 1.27- and 2.00-mm pitch headers.

The same comparison is made for the bridging. For this the comparison can only be made on the 1.50 mm single row pin connector. The soldering of this component was with the de-bridging tool off.

Table 1 - Single header 1.50 mm pitch percentage without bridge

SnBiNiGe (139-190 °C)	SnAgCu (216-219 °C)	SnCuBiNiGe (221-225 °C)
98%	85%	90%

The lower solder temperature for the LTS solder results in less bridging. A possible reason for this is the higher activation of the flux when soldering. For the higher-melting lead-free alloys, the solder temperature of 300°C increases the risk for bridging since flux activation might be significantly reduced at elevated temperatures.

Confirmation with production boards

A full factorial design of experiment is repeated for the SnBiNiGe alloy on production boards to confirm the results of the Box Behnken experiment. These boards were 1.6 mm thick and had an ENIG (Electroless Nickel Immersion Gold) finish. This finish has a good oxidation resistance. The flux used was a no clean REL0 with 2.7% of solids. The board contained three 2.00 mm fine pitch connectors and another 74 leads with a 2.54 mm pitch per board. To minimize the number of runs the drag speed was selected at two levels, 3 and 6 mm/s. The boards were soldered with the 3D printed non-wettable 4 mm square nozzle. This relatively small nozzle was able to solder all connectors in one drag.

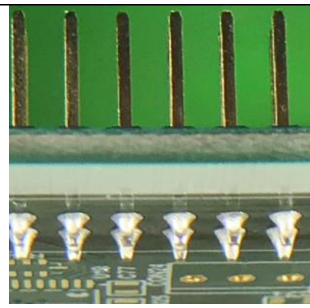
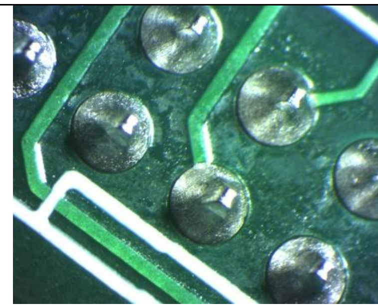
		
The 3D nozzle	Nice solder joints	Excellent 2.00 pitch soldering

Figure 15 - Excellent soldering for solder temperature >240 °C.

Just like in the first experiments the soldering for this alloy was good when the solder temperature was >240°C. The hot nitrogen gas from the SDC was not able to remove all bridges but does return a very nice solder meniscus when the settings are correct.

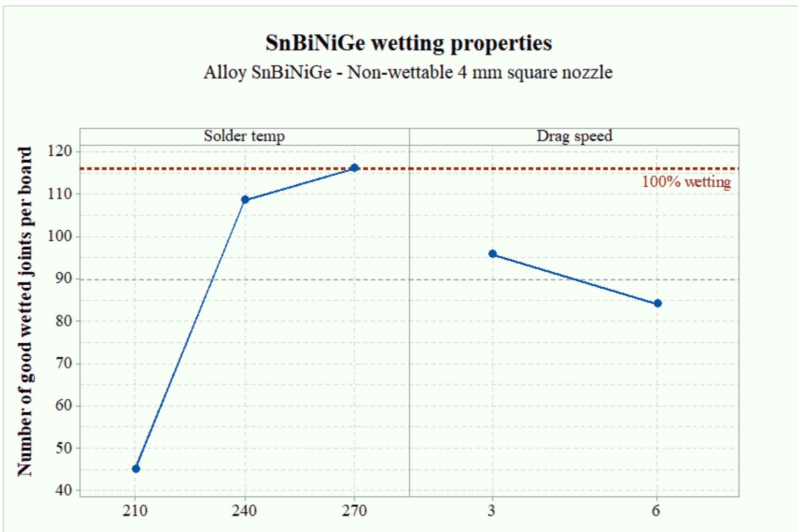


Figure 16 - 100% wetting at 270°C and at 240°C for lower drag speed.

Very interesting was the soldering at 210°C. Although this alloy has a melting range that starts at 139°C, the 210°C superheat is too low to have good wetting. At a low drag speed of 3 mm/s the solder starts to wet the metal surfaces. There is not enough thermal heat to make the solder joint confirm the IPC-A-610 requirements.

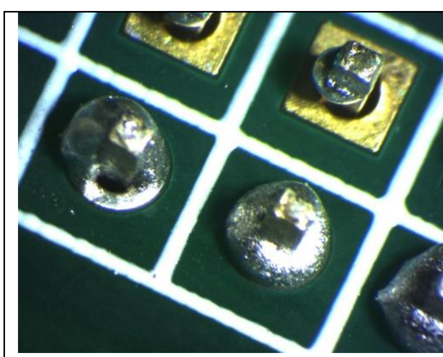
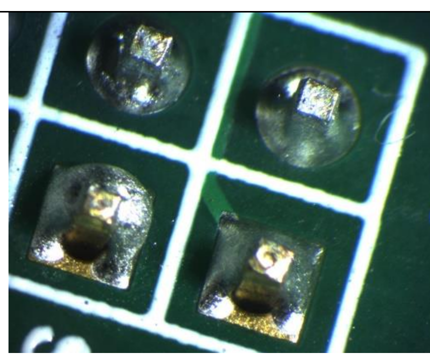
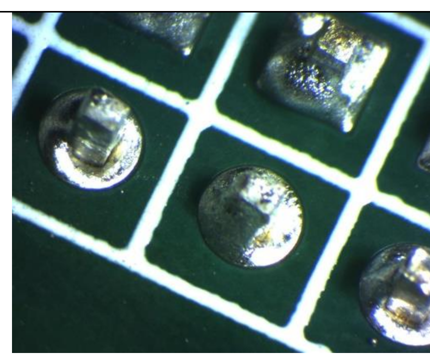
		
Temperature 210°C, 3 mm/s drag. Some leads are not wetted, and some have fat joint.	Temperature 240°C, 3 mm/s drag. The solder source side should be 75% wetted.	Temperature 270°C, 3 mm/s drag. This component is very hard to solder even at 270°C.

Figure 17 - Soldering at different temperatures.

To have a complete wetting there should be enough heat in the assembly. The preheat temperature on topside of the board was 110°C. Higher preheat settings may improve the wetting but the flux activation may reduce when these temperatures are higher.
In this example a wider nozzle like 6 or 8 mm will bring sufficiently more heat in the board since the solder is a good heat conductor.

Conclusions

Selective soldering through-hole components with low melting solder is interesting for multiple reasons including less warpage, risk for fillet/pad lifting, better hole filling, lower material cost and dross reduction. From a reliability point of view, through-hole connectors are up to 20x stronger than SMD components. The solder joints made with this lower melting alloy are strong enough for a wide range of products but are not reliable for products in harsh environments.
Selective soldering with the tested alloy is feasible at temperatures >240°C.

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