New approach for High Reliable & Cost-Effective Solder alloys for Automotive Applications

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Abstract

Commercially known as Innolot, the highly reliable lead-free alloy, allowing for high operating temperatures, is a Tin-Silver-Copper (SAC) metallurgical system with additional elements to harden the alloy and to improve its creep strength in order to significantly improve the reliability of solder joints. Compared to traditional SAC alloys, the characteristic lifetime can be enhanced on the base of temperature cycle tests (TCT) from -40°C to +125°C or even extended to 150°C.

Assemblies in the automotive industry increasingly require higher reliability for safety relevant and emerging applications such as Advanced Driver Assistance Systems (ADAS). Cost-reduction requirements demand a new approach for optimized soldering processes and materials. As the current reflow process prefers Nitrogen atmosphere for low defects in high reliability soldering, our research focuses around the partial and/or complete change to air soldering processes. Furthermore, we investigate the influence of different surface finishes such as Chemical Sn, NiAu, and Cu OSP, and modified alloy compositions in the soldering performance. Apart from initial characterizations for various assemblies, reliability tests on Heraeus Reliability1 printed circuit boards as well as temperature cycle tests from -40 to +150°C for up to 2500 cycles are reported and resulting failure modes are discussed.

This paper furthermore describes the potential for cost reductions via process and/or material optimizations without diminishing the high reliability performance for such automotive applications.

Key words

ADAS, Automotive Safety Applications, Cost Effectiveness, High Reliability Solder, Innolot.

1. Introduction

Due to the growing trends to more electrified, autonomous, and interconnected driving vehicles the assemblies in the automotive industry increasingly require higher reliability for safety relevant and emerging applications such as ADAS. The highly integrated ADAS controllers together with engine control units (ECUs) are the core of the assistance system, which receives data from various cameras, lidars, radars and further sensors for perception and fast safety-critical decision making. Therefore, the long-term reliability of the essential solder joints together with increased temperature requirements are critical for these critical electronic components, as they play an essential role in the safety for all road users, including pedestrians.

The highly reliable lead-free Tin-Silver-Copper (SAC) based alloy with the additional elements Antimony, Bismuth and Nickel, commercially known as Innolot, allowing long term and high temperature requirements, as the hardened alloy composition improves its creep strength in order to significantly advance the reliability of solder joints [1]. Compared to traditional SAC alloys, the characteristic lifetime can be enhanced on the base of TCT from -40°C to at least +150°C.

While increased safety is wanted, cost-reduction requirements are demanded just as well to make ADAS available for the broader automotive market. Therefore, this paper displays new approaches for optimized soldering processes and materials. Especially, as the current reflow process for Innolot prefers Nitrogen atmosphere, our study investigated the partial and/or complete change to air of the reflow soldering process. Furthermore, we examined the influence of different surface finishes such as Chemical Sn, NiAu, and Cu OSP, and modified alloy compositions on the Voiding and Blowhole evolution to understand the influence

on soldering performance and furthermore evaluate the potential for cost reductions as a result of process and material optimizations.
Apart from the soldering investigation on various initial parameters, reliability tests on Heraeus Reliability1 boards with TCT from -40 to +150°C for up to 2500 cycles are reported and resulting failure modes are discussed.

2. Materials and Experimental

This paper aims to present the results from five different solder alloys. Heraeus alloy powders were manufactured using gas atomization and afterwards sieved to comply with IPC solder powder type 4 [2]. The solder alloys used in this study included the well-known, patented Innolot as well as four experimental Tin-Silver-Copper based solder alloys exhibiting a reduced Silver content and containing as additional elements Antimony, Bismuth and further Dopant X to improve the soldering performance during partial and/or complete change to air (Table I) [3].

Table I. Solder alloy composition.

Alloy	Composition
Innolot (Standard)	Sn-**Ag(high)**-Cu-Bi-Sb-**Ni**
High Reliable Solder A	Sn-**Ag(high)**-Cu-Bi-Sb-**X(medium)**
High Reliable Solder B1	Sn-**Ag(reduced)**-Cu-Bi-Sb-**X(high)**
High Reliable Solder B2	Sn-**Ag(reduced)**-Cu-Bi-Sb-**X(medium)**
High Reliable Solder B3	Sn-**Ag(reduced)**-Cu-Bi-Sb-**X(low)**

The solder pastes were prepared from 88 wt.% solder alloy T4 powder and 12 wt.% Heraeus NC flux system. In order to investigate the initial soldering behavior of the Standard Innolot and the High Reliable Solders B2 and B3 we first tested them in Chapter 3.1 on the Heraeus Quick Test Layout (QTL) board (Fig. 1). This FR4 board contains a broad range of different test structures for wetting and slump tests as well as various components such as different passives, BGA, MELF, QFP and TO devices. As variation parameters, three FR4 surface finishes as Chemical Sn, Cu OSP and NiAu were used and in summary, 54 QTL boards were assembled. An ASM DEK Horizon 01i printer with a squeegee length of 170 mm and a pressure of 26 N was used to carry out the printing presented in this report. The thickness of the printing stencil was 120 µm. To investigate further influences of printing to Voids and Blowholes – three printing speeds (30, 50 and 80 mm/s) as well as staging times of 0, 2 and 4 hours after printing were applied before the ASM Siplace X equipment for pick & placement of components was used.

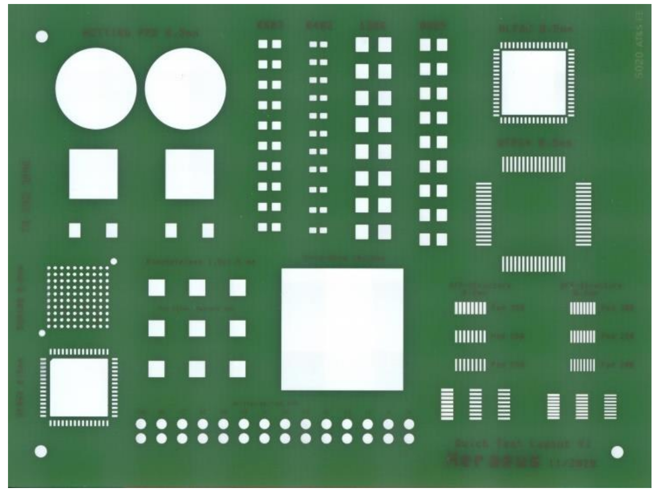


Fig. 1: Heraeus Quick Test Layout (QTL) board.

The soldering reflow process was carried out using a REHM VXS nitro 3150 oven. The Heraeus Lead Free profile with a peak temperature of ~250°C was used as a reflow profile (Fig. 2). In order to analyze the atmosphere influence, three different conditions were investigated – Nitrogen atmosphere with ~1000 ppm and ~5000 ppm residual Oxygen as well as pure air atmosphere for the most challenging situation for area voiding.

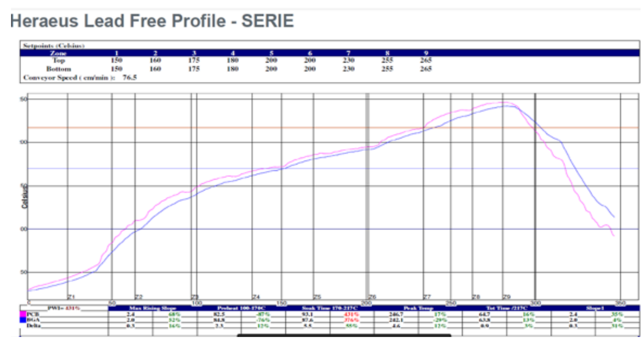


Fig. 2: Heraeus Lead Free reflow profile.

The qualitative analysis of Voids was done using a GE PHOENIX X-ray system and the optical inspection was conducted by a KEYENCE VHX-7000 microscope.

3. Results and Discussion

3.1 Investigation for initial soldering results regarding Voids and Blowholes

As stated in the introduction, the main focus of our initial investigations was on Voids and Blowholes as main output parameters.

Chapter 3.1.1: Initial Soldering Investigations on Voids

The main influence parameters for the total Void level measured via X-ray – for stand-off (under of placed R1206 components) and meniscus Voids (filet at components) – are the FR4 surface finish and the selected reflow soldering atmosphere as well as the interaction of these factors with the solder alloy (Fig. 3).

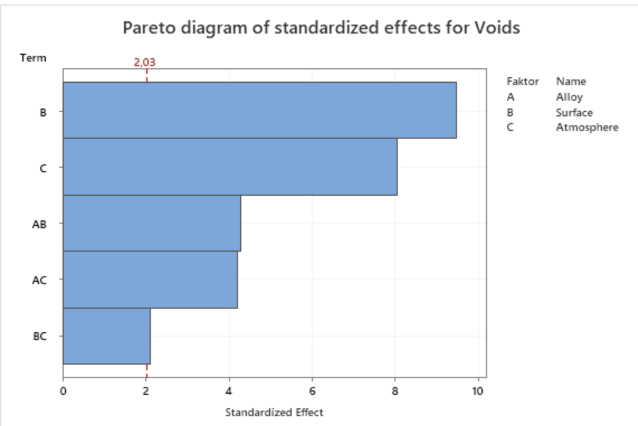


Fig. 3: Pareto Diagram for Voids at R1206 components.

The general voiding trends for the influence of the atmosphere exhibit that soldering in air yields higher void rates than soldering in Nitrogen and it can be also reduced with decreasing residual Oxygen levels. In addition, a very strong influence can be observed for different surface finishes which shows that Chemical Sn yield the highest void rate, followed by Cu OSP and NiAu exhibiting a significant lower level (Fig. 4).

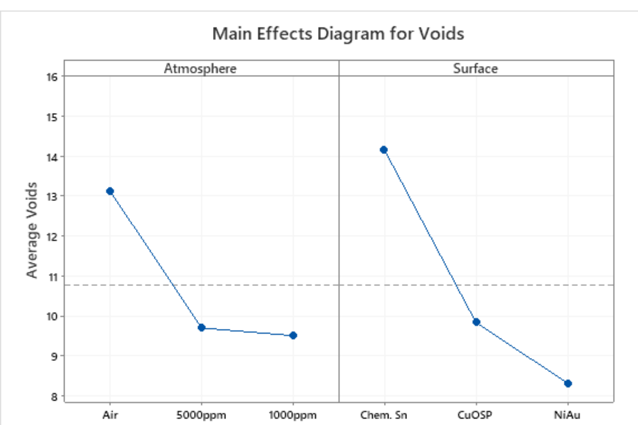


Fig. 4: Main Effects Diagram for Voids below R1206 components regarding Atmosphere and Surface Finishes.

A further goal of this study was to investigate the detailed trends of different solder alloy to voiding. Despite a lower voiding level in different Nitrogen atmospheres (1000 ppm and 5000 ppm residual oxygen) the Standard Innolot alloy seems to be more effected from soldering in air as the new High Rel Solder formulations. The High Rel Solder B3 did not show the lowest, but the most balanced void performance within all tested soldering atmospheres (Fig. 5).

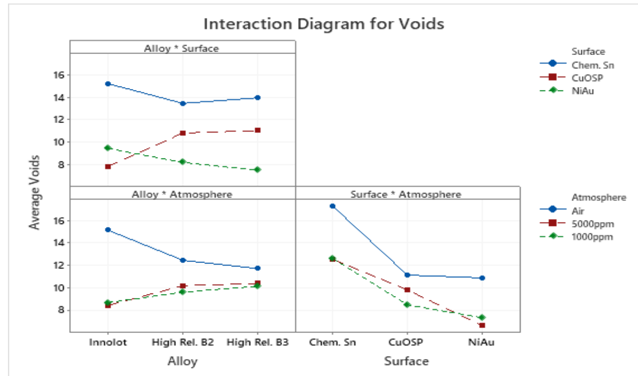


Fig. 5: Interaction Diagram for Voids below R1206 components regarding Alloy, Atmosphere and Surface Finishes

As already mentioned, another strong voiding influence factor is the surface finish of FR4 boards – especially high on Chem. Sn, which, however, cannot be overcompensated from the reflow soldering atmosphere. Other parameters as printing speed and waiting time after printing however did not reveal significant trends to voiding. (Fig. 6).

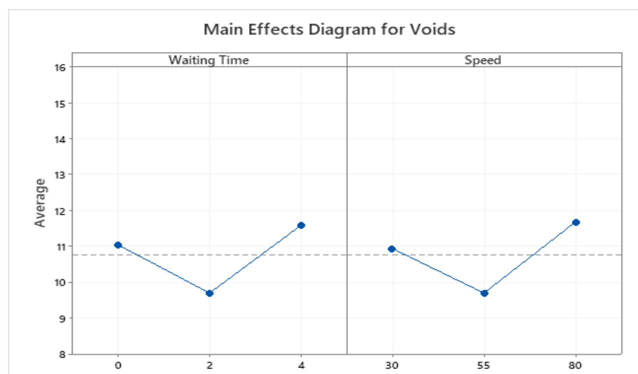


Fig. 6: Main Effects Diagram for Voids at R1206 components regarding Time after Printing and Speed.

Chapter 3.1.2: Initial Soldering Investigations on Blowholes

In addition to the main parameters on Voids also the influence factors on Blowholes are analyzed on the non-populated R1206 pads of QTL board. Even if there is no general definition of Blowholes in the electronic community available, we would like to define them as “open cavities in the solder joints”, which can be detected by optical microscopes (Fig. 7).

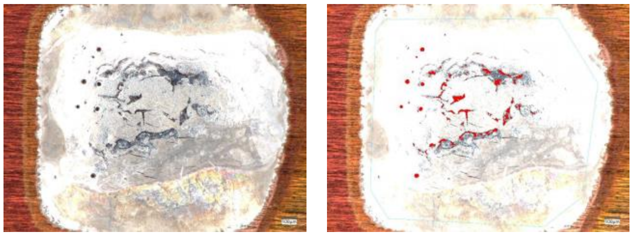


Fig. 7: Optical pictures of non-populated, open solder pads. Left: Original; Right: Blowholes in solder marked in red.

The origin of such open structure (or Blowholes) can be attributed to different effects resulting from both main solder paste components – flux and alloy – as described partially also in the iNEMI solder voiding study [4]. The flux effect is generally explained by the gas evolution of their volatile ingredients or reaction/decomposition products and commonly described as frozen open Macro Voids. The alloy contribution however can have different root causes. The most significant effect is often called alloy Shrinkage Voids and is caused by the rapid alloy solidification – especially in a multi component system such as Innolot. This can either yield regular open holes or bigger dendritic cavities within the joints. Nevertheless, also partly oxidation of the alloy surface during cool-down can also create rough surfaces with smaller holes if there is no flux present anymore and the outer alloy surface gets quickly solidified.
The aim of this chapter is now to investigate if there is a direct correlation of the measured X-ray Voids with the optically detectable Blowholes (>50 µm). The general formation for (open) Blowholes on the non-populated pads of R1206 components seems to be influenced by the alloy, soldering atmosphere and the FR4 surface finish (Fig. 8).

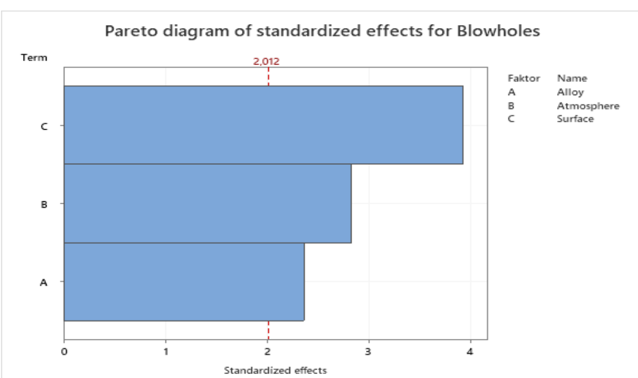


Fig. 8: Pareto Diagram for Blowholes at R1206 open pads.

Overall, the Blowhole formation factors are much less significant as for the Void results. The Blowhole trends are for the atmosphere opposite to the formation of Voids (see Chapter 3.1.1). The general trend for the investigated alloys shows that soldering within air or Nitrogen with ~5000 ppm residual Oxygen yields lower Blowhole rates than soldering in Nitrogen with very low residual Oxygen. An opposite influence vs. Voids can also be observed for the surface finishes, where NiAu finishes yields the highest Blowhole rate, followed by Cu OSP and Chemical Sn exhibiting a significant lower level. (Fig. 9).

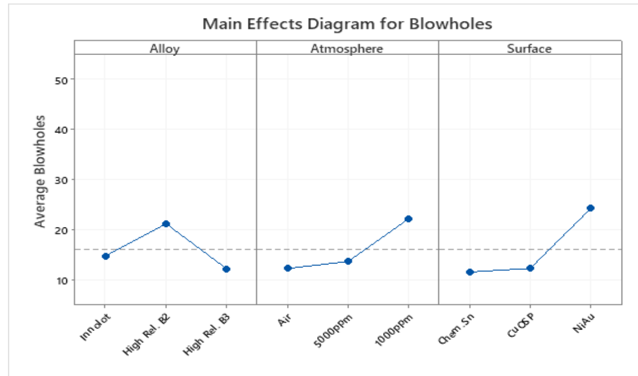


Fig. 9: Main Effects Diagram for Blowholes at R1206 open pads regarding Alloy, Atmosphere & Surface.

Nevertheless, we evaluated the detailed trends for the different investigated alloys on the best and worst surface finish Chemical Sn and NiAu. For QTL boards with the Chemical Sn surface there is a low level and only small influences from different alloys or atmospheres on Blowhole results (Fig. 10).

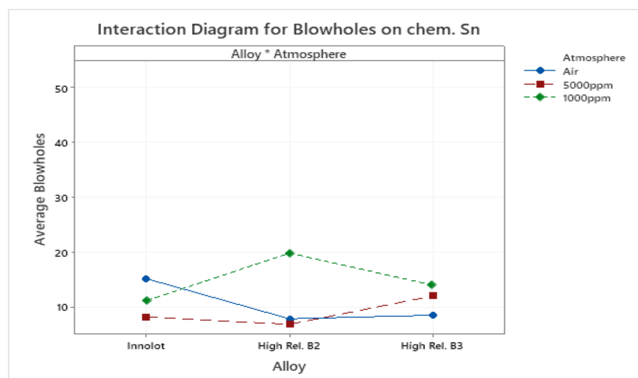


Fig. 10: Interaction Diagram for Blowholes on Chem. Sn.

The QTL boards with a NiAu surface finish however show a higher level – especially in Nitrogen atmosphere with a low-level of 1000 ppm residual Oxygen. These higher variations can be observed for different atmospheres on Standard Innolot, but also the High Rel B2 Solder alloy. The lowest and most consistent Blowhole level is for all atmospheres observed for the High Rel. Solder B3 alloy. (Fig. 11).

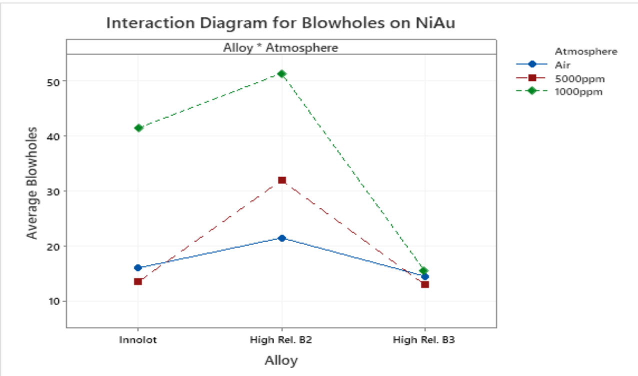


Fig. 11: Interaction Diagram for Blowholes on NiAu.

Other parameters as waiting time after printing and printing speed again did not reveal significant trends for Blowhole level considering the low variations (Fig. 12).

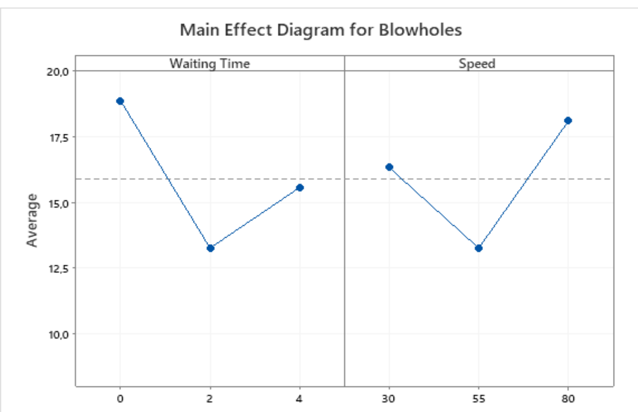


Fig. 12: Main Effect Diagram for Blowholes at R1206 open pads regarding Time after Printing and Speed.

3.2 Temperature cycling tests (TCT)

In order to test the temperature cycling capability between -40 and +150°C for up to 2500 cycles on Heraeus Reliability1 (Rel1) boards were assembled comparing four different solder alloys as shown in Table II.

Table II: Tested alloys for TCT -40/+150°C

Alloy	Ag	Ni	X
Ref. - Innolot Standard	high	medium	-
High Rel. Solder A	high	-	high
High Rel. Solder B1	reduced	-	high
High Rel. Solder B3	reduced	-	low

The four solder alloys were transferred into solder pastes using the same flux system as mentioned in Chapter 2. Afterwards they were reflowed using the Heraeus Lead Free reflow profile in air as shown in Fig. 2. The Heraeus Rel1 boards based on FR4 with chemical Sn surface finish were populated with 16 R1206 resistors to ensure sufficient statistical data. (Fig. 13)

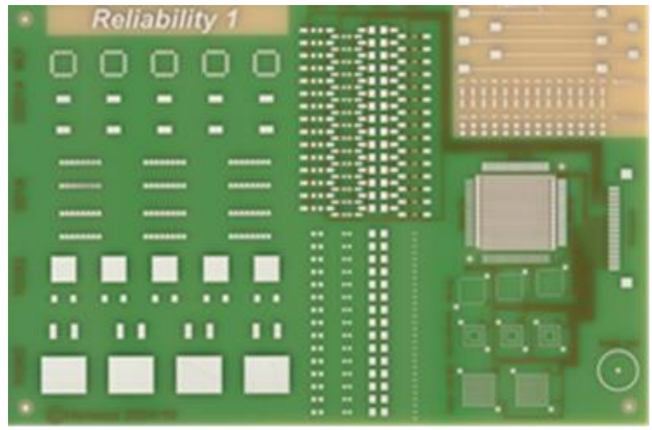


Fig. 13: Heraeus Reliability 1 board.

The -40/+150°C temperature cycling tests were performed in a climate chamber from ESPEC TSA101S-W guaranteeing a total time of 60 mins for each temperature cycle. For shear evaluation, initial and after every 500 temperature cycles 14 of the R1206 components were sheared off using a DAGE 4000, equipped with a load cell of 200 kg.
For the quantitative assessment, a shear force down to 65% of the initial value was considered as good result, which is a rather conservative level to prove a sufficient lifetime for such assemblies. The percentage of "good resistors", fulfilling a shear force of 65% or higher after certain cycles, are plotted in Fig. 14.

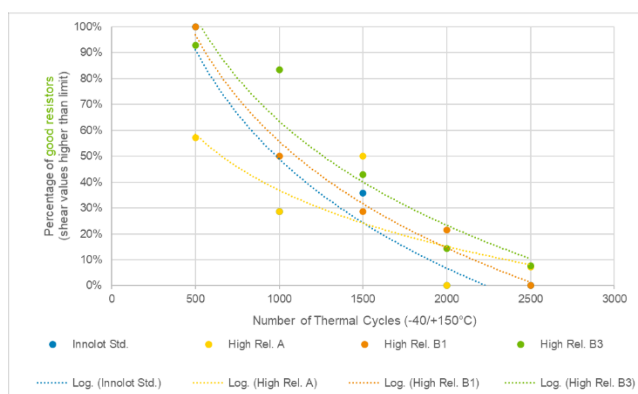


Fig. 14: Percentage of "good resistors" (mean shear force 65% or higher vs. initial value) after TCT at -40/+150°C.

The new developed High Reliability solder formulations with reduced Ag contents show in these TCT data an increased ratio of “good resistors” (>65% of initial shear forces). The High Rel. Solder B3 with the lower dopant X amount gave additionally higher lifetimes than the High Rel. Solders A and B1 containing a high amount of X - both with high and reduced Ag contents. Finally, all new High Rel. Solder formulations outperformed the Standard Innolot.
To explain these results Scanning Electron Microscope (SEM) analyses were performed from R1206 solder joint cross sections before and after 1500 TCT cycles.

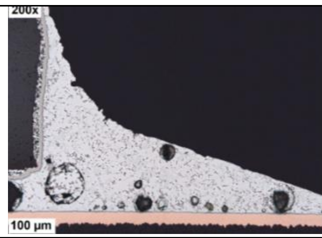
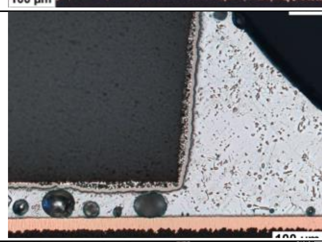
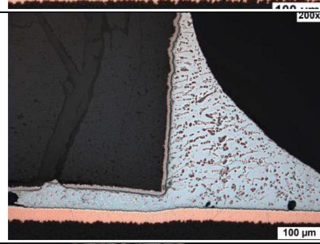
Ref. - Innolot Standard	
High Rel. Solder A (Ag high, X high)	
High Rel. Solder B1 (Ag reduced, X high)	
High Rel. Solder B3 (Ag reduced, X low)	

Fig. 15: SEM pictures of R1206 solder joints before TCT

After 1,500 TCT cycles, the cross sections from the R1206 solder joints show increased crack lengths for the High Rel. Solder versions A and B1 with high amounts of dopant X – independent from high or reduced Ag contents. Furthermore, the SEM pictures of High Rel. Solder B3 alloy show significantly different grain structures than the other cross sections (Fig. 16).

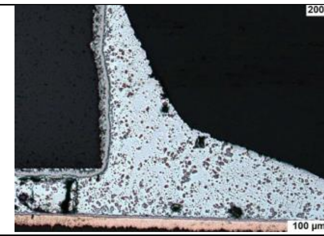
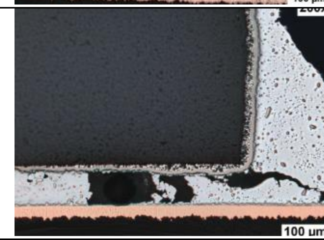
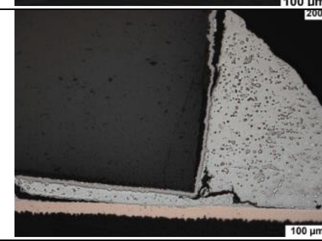
Ref. - Innolot Standard *)	
High Rel. Solder A (Ag high, X high)	
High Rel. Solder B1 (Ag reduced, X high)	
High Rel. Solder B3 (Ag reduced, X low)	

Fig. 16: SEM pictures after 1500 TCT cycles for -40/+150°C; Remark: *) Innolot Std. only after 1000 cycles

These different results can be also illustrated by initial mechanical properties (Table III). The alloys – Innolot Standard and High Rel. Solder A - showed for all mechanical properties tested higher values compared to the favorite alloy High Rel. Solder B3. Therefore, the improved TCT behavior could be attributed to an optimized microstructure as well as decreased hardness and slightly reduced tensile / yield strengths. The ambiguous effects of (too) rigid / hard alloys for TCT results were already discussed earlier and could also explain the improvements in this study [5].

Table III: Mechanical properties of tested alloys.

Alloy Formulations	**Hard-ness H HV0.3**	**Tensile Strength R_m [N/mm^2]**	**Yield Strength $R_{P0.2}$ [N/mm^2]**
Ref. - Innolot Std.	29.7	86.3	60.1
High Rel. Solder B1	30.0	90.1	54.6
High Rel. Solder B3	27.2	79.8	51.4

4. Conclusion

Both studies – the initial soldering DoE as well as the TCT study - show that the choice of the right dopants can ensure at least the same, if not even better performance than the Standard Innolot alloy with a significantly lower metal costing and a pricing potentially closer to SAC 305. The known trade-off between material and process cost vs. the reliability performance was better understood with these studies and can help to select right alloy composition.

Our investigations disclose furthermore that the factors influencing the Void level do not directly correlate to the optical Blowholes formation. In addition, solder Blowholes and surface structures are influenced by a number of other different root causes from alloys, fluxes and the environment. Therefore, the initial performance study on Voids and Blowholes showed a significant improvement with the High Rel. B3 solder alloy especially for reflow processes using increased residual oxygen levels in a Nitrogen atmosphere compared to other high Ag alloys – as Innolot Standard and High Rel. Solder A - even soldering in pure air is possible. Our combination approach of an optimized alloy composition with the broader process window can offer additional cost reductions for safety electronic assembly processes.

For the introduction into cost-sensitive electronic assembly processes further reliability investigations on the advanced High Reliable Solder B3 formulation are ongoing - including temperature cycling/shock tests with additional temperature ranges and broader component ranges as well as drop tests. The outcomes of these studies will be reported in upcoming publications.

Acknowledgment

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