Combined Alloy and Flux Approach Toward Cost-Effective High Reliable Solder Joints for Automotive Applications

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ABSTRACT
Innolot® is a commercially well-known high reliable lead-free alloy suitable for high operating temperatures. It is based on the Tin-Silver-Copper (SAC) metallurgical system and contains additional elements to harden the alloy and to increase 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 TCT from -40°C to + 125°C or even extended to 150°C.

Assemblies in automotive industry increasingly require higher reliability for safety relevant and new emerging applications such as ADAS. Cost-reduction requirements demand a new approach for optimized soldering materials and processes. Our investigations showed that with an improved alloy composition the material cost of our new high reliable alloy can be reduced. Additional cost benefits are achieved by transferring the reflow process to air atmosphere while maintaining high solder joint quality. This break-through was possible due to a combined approach of alloy and flux optimization, which resulted into an innovative high reliable solder paste system.
This paper will show basic alloy and flux properties as well as temperature cycle test (TCT) results comparing the new formulation with SAC305 and Innolot® solder pastes in temperature ranges between -40°C to +125°C as well as +150°C.

Key words: High Reliability Solder, Innolot®, Cost Effectiveness, Automotive Safety Applications, ADAS

1. INTRODUCTION
Due to the growing trend towards more electrified, autonomous driving and connected vehicles, the assemblies in the automotive industry increasingly require higher reliability for safety-related and novel applications such as ADAS. The highly integrated ADAS ECUs, along with the engine control units (ECUs), are at the heart of the assistance system, receiving data from various cameras, lidars, radars and other sensors for perception and rapid safety-critical decision making. Therefore, long-term reliability of key solder joints, along with increased temperature requirements, is critical for these critical electronic components as they play an essential role in the safety of all road users, including pedestrians.

The highly reliable lead-free tin-silver-copper (SAC) based alloy with the additive elements of antimony, bismuth and nickel, known in the market as Innolot®, enables long-term and high-temperature requirements as the hardened alloy composition improves creep resistance to significantly increase the reliability of solder joints [1]. Compared to conventional SAC alloys, the characteristic lifetime based on TCT can be increased from -40°C up to 150°C.

While safety is to be increased, cost reduction requirements are equally imposed to make ADAS available for the broad automotive market. Therefore, new approaches for optimized soldering processes and materials are highlighted in this paper. Since the current reflow process for Innolot® is preferentially performed under nitrogen atmosphere, our study investigated the partial and/or complete conversion of the reflow soldering process to air as well as changed alloy compositions on void and void development to understand the impact on soldering performance and furthermore to evaluate the potential for cost reductions through process and material optimization.

In addition to soldering studies at various initial parameters, reliability tests on Heraeus Reliability1 boards with TCT from -40 to +150°C for up to 2500 cycles are reported and the resulting failure modes are discussed.

Cost Effective Manufacturing
The levers for cost-efficient manufacturing in this paper and in the area of PCB assembly in combination with the use of solder paste can be separated into material costs and process costs. Changing requirements call for new solder alloys, which can be more difficult to handle compared to SAC alloys. A six-element alloy such as Innolot® behaves differently during melting and solidification compared to a three-element alloy such as SAC305. This can lead to undesirable and sometimes unacceptable defects such as voids and cavities due to the increased complexity of the material during melting and solidification.

One way to reduce the aforementioned defects is to add a high amount of nitrogen to the reflow oven atmosphere. A cost-effective manufacturing approach must provide the ability to reduce the defects, even without the need to add nitrogen to the reflow oven. This would allow users to reduce or even eliminate nitrogen in the reflow oven to save process costs. Production lines that do not yet have additional nitrogen available could avoid adding the inert gas to the production line.

A look at the material composition of Innolot® shows that silver has a high impact on the material costs with ~3.8% of the composition. It contains an even higher silver content than SAC305. In terms of a cost-effective approach to high-reliability materials, silver content has a high potential to reduce material costs. Nevertheless, reliability performance must be at a similar level to Innolot®.

In addition, a cost-effective approach must also consider the raw material supply chain. Impurities can affect SIR performance and lead to electrochemical migration, causing potentially costly application problems. Variations in natural ingredients can affect batch-to-batch performance and lead to yield losses in production. Therefore, the approach taken here is to use synthetic ingredients instead of natural ingredients such as rosin.

In the following sections, the approaches to reduce defects in air atmosphere without additional nitrogen, to reduce material costs while maintaining the high reliable properties of Innolot® and to use fully synthetic resins are explained in more detail.

2. MATERIALS

This paper aims to present the results from different solder alloys and fluxes developed at Heraeus. 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 patented Innolot® as well as three 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 air soldering performance (Table 1) [3].

Table 1. 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 B3	Sn-**Ag(reduced)**-Cu-Bi-Sb-**X(low)**

For optimization of the air soldering performance, a newly developed flux was used, which was optimized to address specifically soldering defects such as blowholes, voiding and viscosity. In addition to that, raw materials which show a risk to impurities and supply, specifically naturally sourced compounds such as colophony-based resins and certain amines were replaced by fully synthetic materials, e.g. an acrylic resin, to reduce potential deviations in product quality and performance. The soldering behavior was referenced against a common Heraeus standard flux. The solder pastes were prepared from 88 wt.% solder alloy T4 powder with 12 wt.% of different Heraeus NC flux systems.

In order to optimize the solder alloy for temperature thermocycling between of -40/+150°C different high reliable solders and as reference the standard Innolot® was first tested with a Heraeus standard no-clean flux on the Reliability 1 board described in chapter 3.

After identifying the best solder alloy further optimizations of the initial printing and soldering behavior of the high reliable solders B3 and as a reference the standard Innolot® with different flux systems were done on the Heraeus Quick Test Layout described in Chapter 4.

In both cases an ASM DEK Horizon 01i printer with a squeegee length of 170 mm, a pressure of 26 N and a printing speed of 50 mm/s was used to carry out the printing presented in this report. The thickness of the printing stencil was 120 µm. Afterwards the ASM Siplace X equipment was used for pick & placement of components. The soldering reflow process was carried out using a REHM VXS nitro 3150 oven. The Heraeus lead free reflow profile with a peak temperature of ~250°C was used as can be seen in Fig. 2 and an air atmosphere was applied.

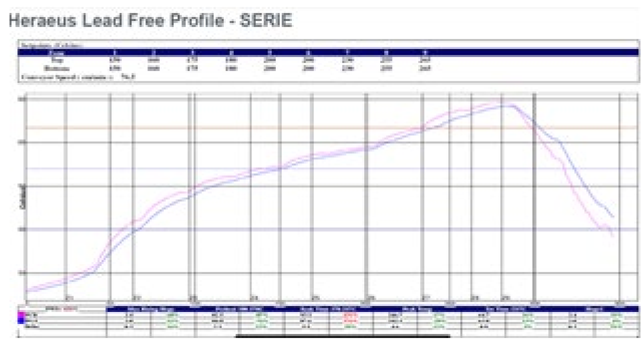

Figure 1. Heraeus Lead Free reflow profile

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. HIGH RELIABLE SOLDER ALLOYS – RESULTS & DISCUSSION

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 type 4 solder pastes as described in chapter 2. The Rel1 boards based on FR4 with chemical Sn surface finish were populated with 16 R1206 resistors to ensure sufficient statistical data. (Fig. 2)

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.

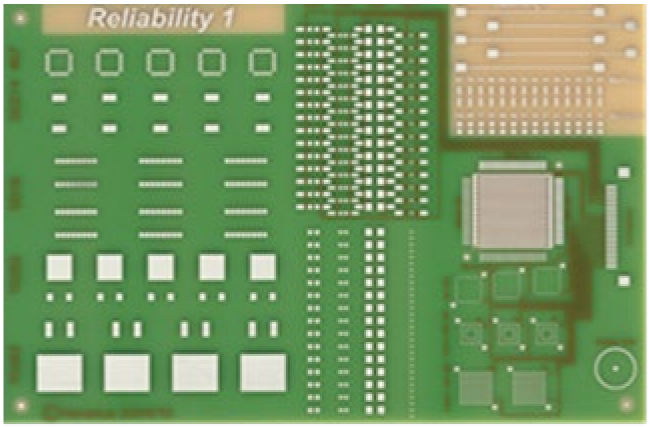

Figure 2. Heraeus Reliability 1 board.

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. 3.

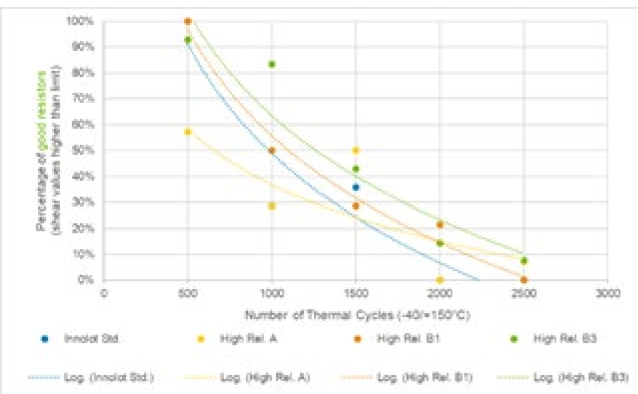

Figure 3. Percentage of “good resistors” (mean shear force 65% or higher vs. initial value) after TCT at -40/+150°C.

The new developed high reliability solder formulations with reduced Ag contents show in these TCT data an in-creased 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 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 (Fig. 4).

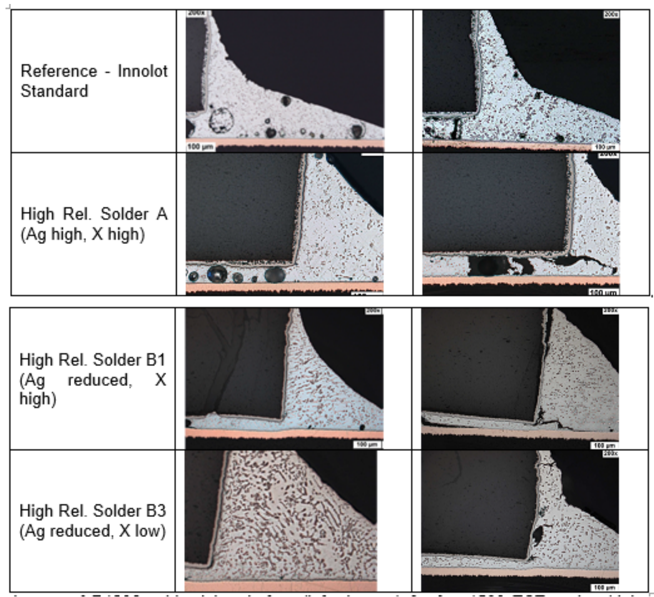

Figure 4. SEM pictures of R1206 solder joints before (left pictures) & after 1500 TCT cycles (right pictures) for -40/+150°C; Remark: Innolot® Std. only after 1000 cycles.

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.

These different results can be also illustrated by initial mechanical properties (Table 2). 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.

Table 2. Mechanical Properties of Tested Alloys.

Alloy Formulations	Hardness H HV0.3	Tensile Strength R_m [N/mm²]	Yield Strength $R_{P0.2}$ [N/mm²]
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. HIGH RELIABLE SOLDER PASTE – RESULTS & DISCUSSION

Solder Pastes using our new fully synthetic flux were characterized regarding their solderability and voiding behavior in an 100% air atmosphere and resulting defects using type 4 Innolot® and the new high reliability solder B3 by maintaining key properties such es excellent printability and SIR reliability.

Improved Soldering Appearance

Soldering performance in a 100% air atmosphere is advantageous as protective gases significantly increase cost in production. Innolot® is typically soldered in a nitrogen atmosphere as it tends to show a significant drop in quality when soldered in air. A pure air atmosphere can cause “blowholes”, wetting and voiding issues. These defects can be strongly influenced by the flux. Figure 5 shows the results of IPC 650 tests of several Heraeus standard solder paste with two different fluxes and alloys. The conventional flux shows with Innolot® a strong tendency to blowhole formation in air. In contrast, the new flux leads to a significantly improved surface, increased wetting and class 1 solder balling for Innolot® as well as the new High Reliability Solder alloy B3.

Figure 5. IPC 650 tests in 100% air atmosphere: Conventional flux with Innolot® (left); new flux with Innolot® (middle); new flux with High Rel. Solder alloy B3 (right).

For the further tests the Heraeus Quick Test Layout (QTL) FR4 board was used, which exhibits a chemical Sn finish and 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 (Fig. 6).

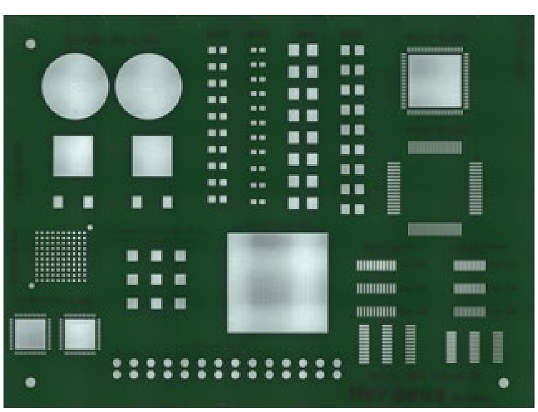

Figure 6. Heraeus Quick Test Layout (QTL) board.

Figure 7 shows a comparison of a solder joint of a CR0402 component on the QTL board using Type 4 Innolot® pastes soldered in air. The joint of the reference paste (left) appears in a very rough surface characterized by many blowholes of different sizes. In contrast, the solder joint using the newly developed flux shows a significantly smoother surface with a significantly reduced number of blowholes. This result can further be improved using the new High Reliability Solder alloy B3 in combination with the new flux.

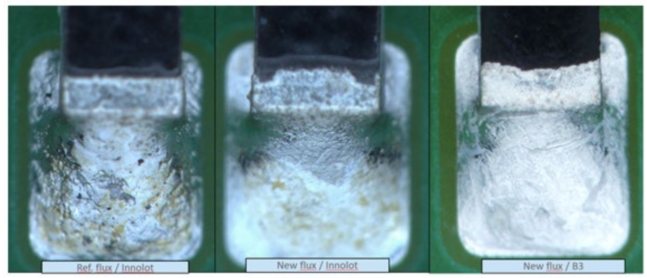

Figure 7. Solder joints of a CR0402 component: Conventional flux with strong holes (left); new flux with Innolot® (middle); new flux with High Rel. Solder alloy B3 (right).

Lower Voiding Behavior

A main concern when soldering in air is the voiding behavior.

For BGA voiding and especially large area components, an increase in voids can be observed and can easily be outside the IPC requirements of about 50%. Therefore, the voiding behavior of the new flux system has been optimized for a variety of typical large area SMD com-ponents. Figure 8a & Figure 8b show the comparison of different pastes using type 4 Innolot® to the new flux in terms of BGA and area voiding behavior. BGA voiding shows a very good performance of below 1% for all pastes. However, the new flux can slightly improve the voiding. The strongest influence on BGA voiding is the change to the new high reliability alloy B3 in combination with the new flux. Almost no BGA voiding can be observed for this paste. The strongest influence on voiding was observed for area voiding of large area components (Figures 8a & 8b).

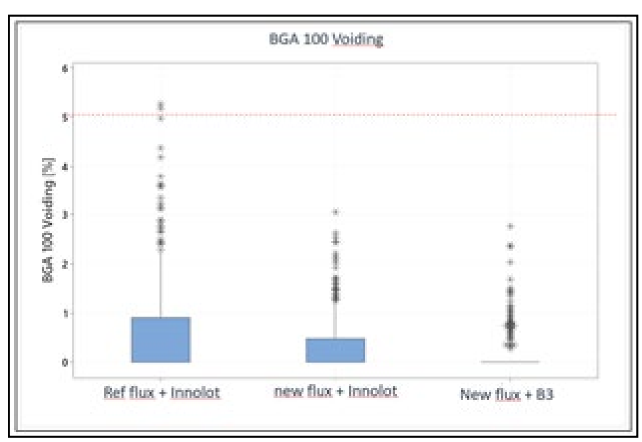

Figure 8a. BGA Voiding Chart with the new flux system in combination with Innolot® and the B3 alloys

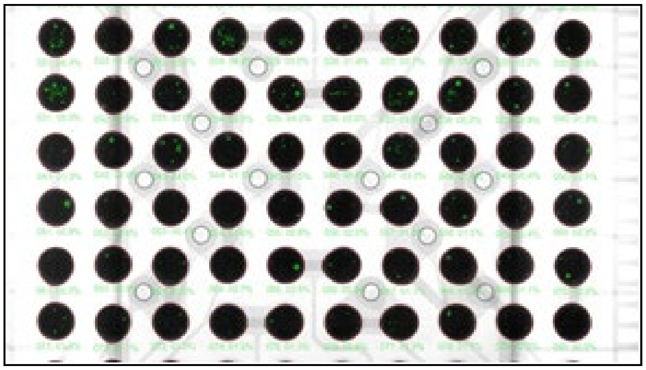

Figure 8b. X-ray of BGA Voiding with the new flux system in combination with Innolot® and the B3 alloys

Three pastes were tested with MLF 48 and MLF 68 components which the combination of different flux types and alloys without any optimized stencil layout. The reference Innolot® paste shows a critical performance in terms of area voiding of nearly 50%.

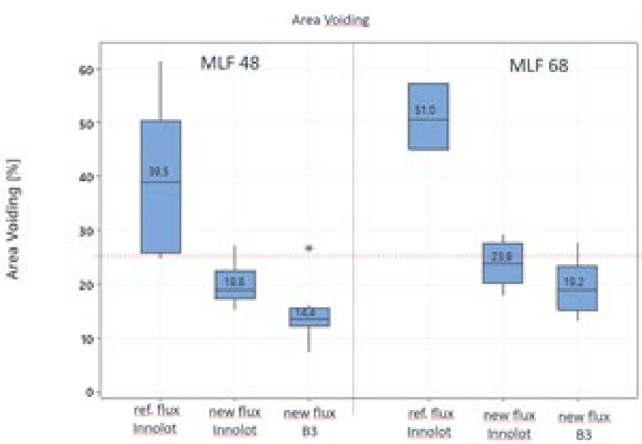

Figure 9a. Area Voiding Chart under MLF48 & MLF 68 system in combination with Innolot® and the B3 alloys

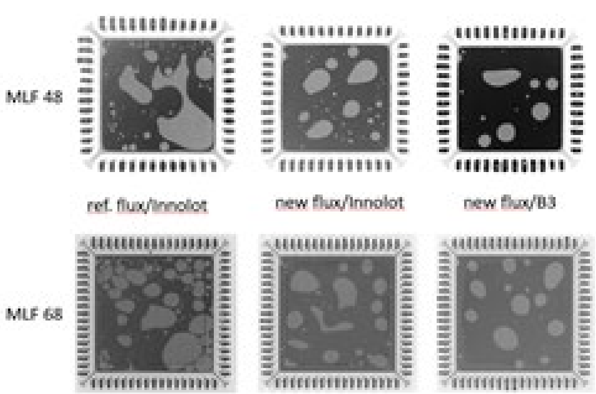

Figure 9b. X-ray of Area Voiding under MLF48 & MLF 68 system in combination with Innolot® and the B3 alloys

The new flux system in combination with the standard Innolot® shows a significant improvement. Area voiding could be reduced to 20% for MLF 48 components and 24% for MLF 68 components. Using the new High Reliability Solder alloy B3 in combination with the new flux further improves the voiding for both area components (Figures 9a & 9b).

Increased Paste Stability

Solder pastes typically tend to increase in viscosity and yield point when stored at room temperature and above. This can negatively impact printing performance and the change in viscosity might have a negative impact on printability or screen life. The usage of the fully synthetic resin instead of colophony shows an improved stability at room temperature. This potentially reduces the risk of a viscosity change during shipment of the paste and easier handling of the material. The viscosity of the reference paste drifted about 20% course of 7 days at 30°C. The yield point increased about 58%. The paste using the new flux formulation shows a significantly improved stability for viscosity and yield point as can be seen in Figures 10a & b.

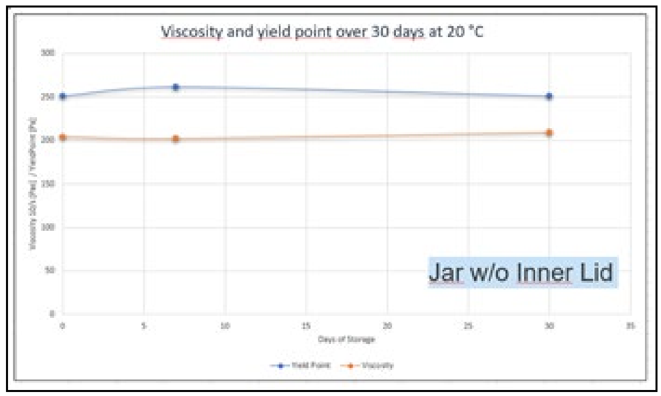

Figure 10a. Viscosity and yield point of the new flux with Innolot® over 30 days at 20°C

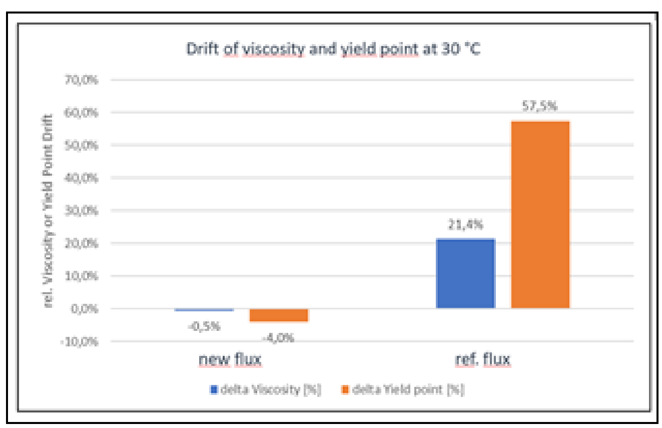

Figure 10b. Viscosity drift and yield point of the new flux with Innolot® and relative change in 7 days at 30°C.

Surface Insulation Resistance (SIR)

Surface Insulation Resistance (SIR) is the electrical surface resistance of an insulating surface. The SIR testings are quantitative methods to determine possible electrochemical reactions at or below the surface of electronic circuits. They are affected by the components used there as solder paste residues after reflow on specific PCB boards with a layout of 200 µm lines and 200 µm spaces shown in Figure 11.

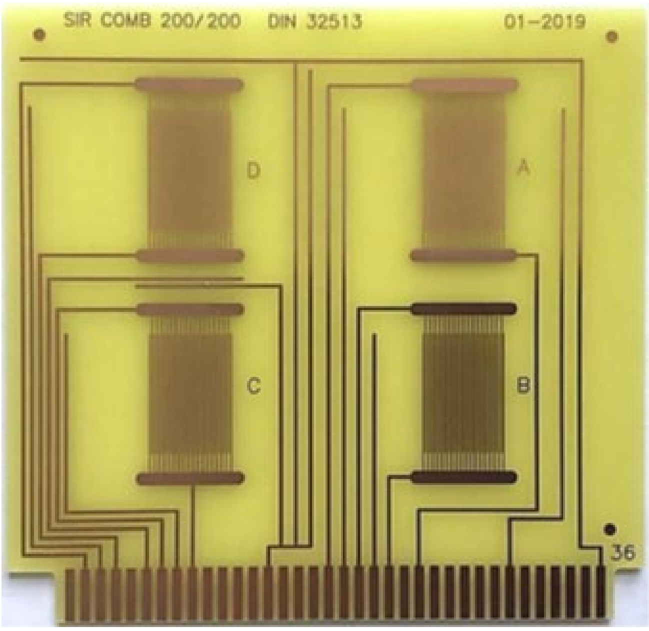

Figure 11. 200/200 SIR Comb

The SIR tests of the high reliability solder alloy B3, in combination with new fully synthetic flux system were carried out by the National Physical Laboratory UK. Therefore, two sets of PCBs were SIR tested under two climatic conditions, (40°C/93% r.H. and 85°C/85% r.H.) for 1000 hours. For each climatic conditions, the PCBs were held vertically using edge connectors in the chamber, as shown in Figure 12.

Figure 12. Positioning of combs in SIR chamber.

The first measurement for all the PCBs, was taken under ambient conditions at 22°C/40% r.H. with 100 V bias applied to the samples. After this measurement, to avoid condensation the chamber temperature was raised over 30 minutes and then the humidity was increased over a further 30 minutes. The 50 V DC conditioning bias was maintained throughout the 1000 hours tests. The SIR was measured every 30 minutes at 100 V. 100 V measurement voltage was applied for one minute before each SIR measurement. The equipment used for the SIR measurements was an Auto-CAF2 supplied by GEN3 Systems which has the capability of measuring down to ~10^4 Ω. The open circuit resistance at 100 V was at least 10^{12} Ω.

The results of both testing conditions show that the new flux system passed the requirements. All channels below show stable behavior above $1*10^9$ Ohm (Figure 13a & b). As the SIR test board assembly was not executed in a clean room, but under real conditions as in typical PCB assembly single fibers, e.g. from cleaning tissues of the solder paste printer, were present. It was carefully checked under the microscope that slight resistance drops at single channels are due to fiber contaminations, and not due to dendrites.

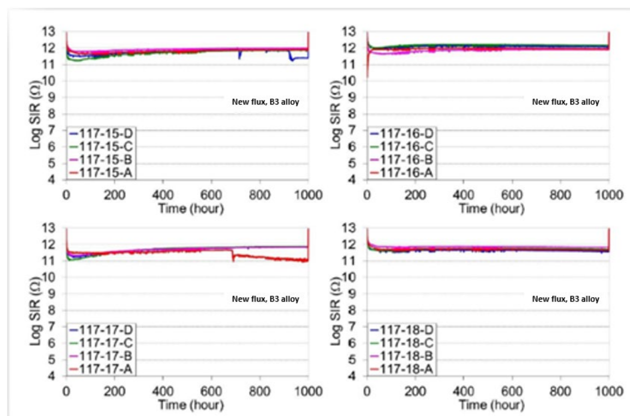

Figure 13a. SIR results (40°C/93% r.H. – 1000 hours)

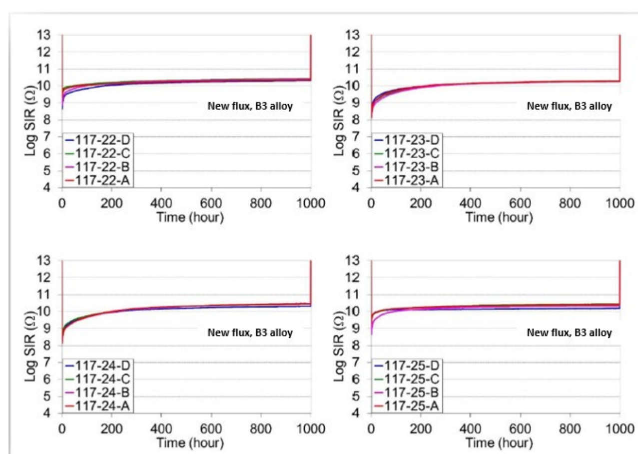

Figure 13b. SIR results (85°C/85% r.H. – 1000 hours)

5. SUMMARY AND OUTLOOK

The above reported results from the development of a high reliable solder alloy as well as the corresponding solder paste show that the choice of the right dopants and flux chemistry can ensure at least the same, if not even better performance than the Standard Innolot® alloy with a significantly lower metal costing. The known trade-off between material and process cost vs. the reliability performance was better understood with these studies and can help to select the right alloy composition.

Therefore, the initial performance study on voids and blowholes showed a significant improvement with the high rel. solder alloy B3 especially for reflow processes in air atmosphere compared to other high Ag alloys – as Innolot® - even soldering in pure air is possible. In addition to the optimized Innolot® alloy, a new flux system could be developed which significantly improves solderability of Innolot® alloys in an air atmosphere and is able to achieve a performance close to a process using a nitrogen atmosphere. Both, the improved Innolot® alloy and the new flux system in combination provide the potential to reduce process costs by decreasing nitrogen consumption.

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 tests with additional temperature ranges and more detailed evaluations. The results of these studies will be reported in upcoming publications.

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