A Drop-in High-Temperature Pb-Free Solder Paste that Outperforms High-Pb Pastes in Power Discrete Applications

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Abstract
Sn-based high-temperature lead-free (HTLF) solder pastes have been developed as a drop-in solution to replace the high-Pb solder pastes in power discrete applications. The pastes were designed to combine the merits of two constituent powders. A SnSbCuAg powder, with the melting temperature above 320˚C, was designed to maintain a high-temperature performance. A SnAgCuSb powder, with a melting temperature around 228˚C, was added to the paste to enhance wetting and improve joint ductility. In the design, the final joint will have the low-melting phase (the melting temperature >228ºC) in a controllable quantity embedded into the high-melting SnSbCuAg matrix. HTLF-1, one of the designs, maintained the bond shear strength up to 15MPa, even around 290˚C. Another design, HTLF-2, has a similar bond shear strength as Pb92.5/Sn5/Ag2.5 around 290˚C, but exceeds substantially below 250˚C. The power discrete components had been built with both HTLF solder pastes for both die-attach and clip-bond through the traditional high-Pb process, which demonstrated the drop-in processing compatibility. The components survived three additional SMT reflows (peak temperature of 260˚C) and passed moisture sensitivity level 1. This confirmed that the maintained joint strength (comparable to or stronger than high-lead), helped to keep the joint integrity within the encapsulated components, even with melting phases in a controllable quantity existing above 228˚C. Both HTLF solder pastes outperformed Pb92.5/Sn5/Ag2.5 in RDS(on) even after 1000cycles of TCT (-55/175ºC), which is attributed to the intrinsic lower electrical resistivity of Sn of both HTLF pastes. Microstructural observation had shown no corner cracks for both die-attach and clip-bond joints after TCT.

Key words
lead-free solder, power discrete, temperature cycling, die-attach, Durafuse™

I. Introduction
Development of high-temperature Pb-free (HTLF) solder pastes to replace high-Pb (Pb>85wt%) solders for die-attachment in power device applications is driven by (1) the harmful effects of lead on human health and the environment (RoHS, WEEE, etc.), and (2) the demand for improved performance for higher efficiency. The current exemption of high-lead solders is expiring in 2024. However, an extension of the exemption is possible because the drop-in solution is still in its infancy stage due to the combination of processing, performance, maturity, and cost.

The major requirements for HTLF solder pastes for power discrete applications (die-attach and clip-bond) include: (1) a re-melting temperature higher than 260°C to maintain joint integrity while undergoing subsequent SMT reflows, (2) a service temperature of 150°C or higher, (3) a drop-in solution compatible to the current high-lead soldering and subsequent packaging processes, (4) good thermal fatigue resistance, (5) comparable or even superior electrical/thermal performance to high-lead solders, and (6) relatively low cost. Efforts for seeking a drop-in solution with improved performance have been attempted for more than two decades. The HTLF solder candidates include (1) AuSn/AuSi/AuGe, (2) ZnAl-based, (3) BiAg/BiCu/BiAgX, and (4) SnSb, etc. In addition to a solder alternative, sintering, semi-sintering, and Ag-epoxy options have also been attempted for many years. However, each of the candidates satisfied only the niche application [1, 2].

II. Design of the paste
Indium Corporation has been developing the novel Sn-based high-temperature Pb-free (HTLF) solder pastes, which are targeted as offering a drop-in paste solution and outperforming the current high-lead solders for industry

usage. The current HTLF pastes combine the merits of both SnSb-based high-temperature alloys (solidus temperature at 326°C) and the commonly-used Sn-rich (Sn>85wt% and solidus temperature >217°C) solder alloys. The final joint will be dominated by Sn and be alloyed mainly with Sb, Ag, Cu, and the doping elements. The selected combination is expected to deliver better thermal conductivity and less electrical resistivity than high-Pb since Sn is intrinsically superior to Pb in thermal and electrical performance.

SnSb-based high-temperature alloys [1] have a solidus temperature at 326°C and a liquidus temperature around 366°C, shown in Figure 1. The 366°C liquidus temperature is 30–40°C higher compared to high-Pb solders, which need the higher reflow temperature during soldering. SnSb-based high-temperature alloys (dominated by SnSb IMC compounds) are strong and rigid, which may risk shattering large-sized Si die if reflowing under the high peak temperature profile [1-4]. Sn-rich solders are much more ductile and have a relatively low- melting temperature. Combining the high-melting SnSb-based alloys and the low-melting and ductile Sn-rich alloys together is expected to lower the reflow peak temperature and make the joint more ductile in order to reduce the risk of large-sized Si die shattering.

However, the introduction of a Sn-rich alloy in the mixed solder powder paste will retain some of the Sn-rich phase in the final joint, which may render the solder to partially re-melt during the subsequent SMT reflow and lead to solder squeeze-out. This can cause a risk to the integrity of the die-attach and/or clip-bond joints inside the encapsulated discrete. Thus, the quantity of the low-melting Sn-rich phase must be controlled in the final joint to allow it to maintain joint integrity and resist the solder squeeze-out during SMT reflow.

High-Pb solders have successfully been used for die-attach and clip-bond in power discrete for decades. Thus, in order to resist the solder squeeze-out in SMT reflow as high-Pb did, the joint formed with the HTLF solder joints should present the similar or even higher joint strength compared to high-Pb joints during SMT reflow, which has a peak temperature up to 260°C or even higher.

After the proof of concept tests and a dozen rounds of materials screening, two pastes, HTLF-1 and HTLF-2, have been selected for sampling and testing. These have been confirmed as to be able to be processed as a drop-in solution and outperform the high-Pb solders in RDS(on) for the tested power discrete.

III. Results

A. Melting Behavior

Fig. 1 shows the DSC curves of these two HTLF solder pastes: HTLF-1 and HTLF-2, along with a SnSb-based high-temperature alloy. Two separate melting peaks (P1 and P2) in the DSC curves of both HTLF-1 and HTLF-2 are associated, respectively, with the melting behavior of the low-melting Sn-rich phase and the high-melting SnSb phase, while only one high-melting peak from 326°C to 365°C is seen for SnSb-based high-temperature alloy. Compared to SnSb-based alloys, the mixed powder system dramatically changed the melting behavior and the melting peak shifted to a lower temperature, which allows for the lower reflow peak temperature and the feasibility as a drop-in solution.

The area of each peak for both HTLF-1 and HTLF-2 indicates the heat absorption from each of the separated melting behaviors. The ratio of P1 and P2 is used to characterize the proportion of the low-melting Sn-rich phase relative to the high-melting SnSb phase in the final joint. HTLF-1 has a ratio of P1/P2 of ~10% while HTLF-2 has a ratio of ~15%. This indicates that the quantity of the low-melting Sn-rich phase in HTLF-2 is substantially more than that in HTLF-1.

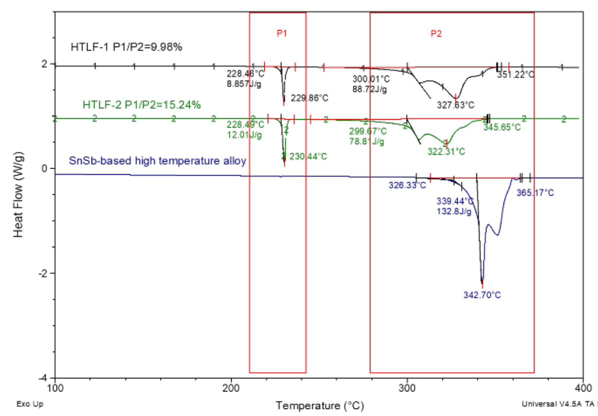


Fig. 1. DSC of HTLF-1, HTLF-2, and SnSb-based high-temperature alloys. HTLF-2 has a lower melting Sn-rich phase than HTLF-1.

B. Bond Shear Strength

A bond shear test was conducted on the Cu/Cu joints, which were reflowed under a traditional high-temperature high-Pb profile. Pb92.5/Sn5/Ag2.5, one of the commonly-used high-Pb solders, decreased the bond shear strength from 30MPa at room temperature down to 5MPa at 290°C. The joint shear strength of HTLF-1 always exceeded 15MPa from room temperature up to 295°C, as shown in Fig. 2, which meets the 15MPa-joint-strength requirement by the DA5 Consortium and is around three-times that of Pb92.5/Sn5/Ag2.5. The bond shear strength of HTLF-2 decreased from around 60MPa at room temperature down to 5MPa at 295°C, which is barely comparable to Pb92.5/Sn5/Ag2.5. As a comparison, the SnSb-based high-temperature alloy maintained a bond shear strength above 40MPa, even around 280°C. Combining a SnSb-based high-temperature alloy with a low-melting Sn-rich alloy decreases the high-temperature strength and increases the ductility, which reduces the risk of large-sized Si die shattering. Indeed, tests of both 5x5x0.105mm^3 Si and 6.8x4.7x0.1mm^3

Si (TiNiAg metallization for both) on Cu-leadframe and clip-bond power discretes (HTLF-1) have passed the drop-in process and TCT reliability test, which will be reported later.

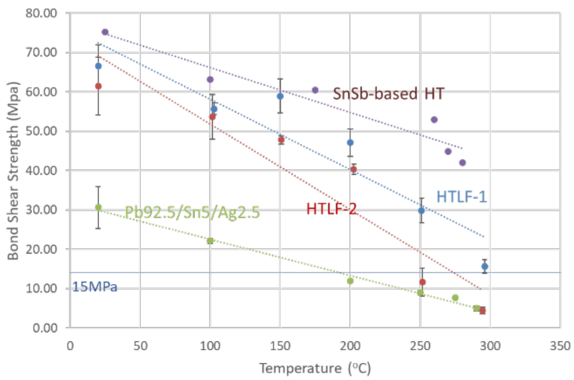


Fig. 2. Bond shear strength of HTLF pastes: HTLF-1, HTLF-2, and Pb92.5/Sn5/Ag2.5.

Recall the existence of the low-melting Sn-rich phase in the paste, which may risk or even damage the joint integrity when soldering the power discrete onto the PCB with traditional SMT reflow. In the design, we are relying on the well-maintained high-temperature strength to reduce the risk and/or the damage of the joint. These two pastes were selected based on their high-temperature (up to 295°C) strength. HTLF-1 maintained the high-temperature (295°C) strength above 15MPa, which is much stronger than high-Pb under the same temperature. On the other hand, HTLF-2 maintained the high-temperature (295°C) strength barely comparable to high-Pb.numerals.

C. Voiding

The encapsulated components consisted of two 2.5x1.6mm^2 Ti/Ni/Ag-Si dies bonded onto two separate pads of a Cu-leadframe. Clip-bond was used to interconnect the die top to Cu-lead with the same solder. During the assembling process, both HTLF-1 and HTLF-2 solder pastes, together with Pb92.5/Sn5/Ag2.5, were used to build the package under the same high-Pb production process (reflow/cleaning/wire bond/molding). The peak temperature of the reflow was 385°C.

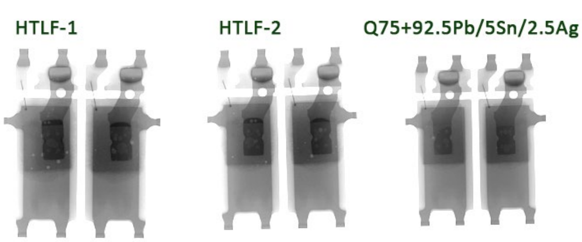


Fig. 3. Voiding performance of both HTLF pastes (HTLF-1 and HTLF-2) and Pb92.5/Sn5/Ag2.5 under the same high-Pb reflow profile with a peak temperature of 385°C.

Voiding levels were studied with X-ray inspection, as shown in Fig. 3. Both HTLF solder pastes (HTLF-1 and HTLF-2) and Pb92.5/Sn5/Ag2.5 have shown comparable voiding levels. Success of using the traditional high-Pb process for both HTLF pastes verifies the drop-in processing compatibility.

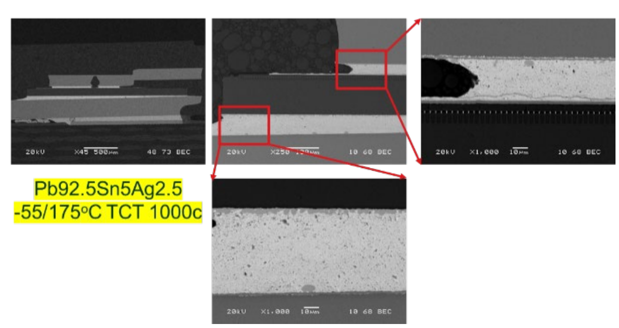
D. Pre-conditioning and Moisture-Sensitive Level Tests

The moisture-sensitive level (MSL) tests on the components were conducted by following IPC/JEDEC J-STD-020D. Both HTLF-1 and HTLF-2 passed MSL-1. The pre-conditioning was done on the encapsulated components with three-times SMT reflow using the peak temperature of 260°C. After testing, ultrasonic scanning did not find any delamination inside the components. RDS(on) had a minute change before and after three-times SMT reflow. This confirms that the sufficient high-temperature strength (>= the joint of high-Pb) does maintain the joint integrity within the encapsulated components after three-times SMT reflow. However, the partial re-melting may still grow the interfacial IMCs slightly and it may be associated with the minute change of RDS(on). RDS(on) of both HTLF pastes were superior to that of Pb92.5/Sn5/Ag2.5, which will be shown later.

E. Temperature Cycling Test

After conducting the MSL tests, temperature cycling tests (-55/175°C) were also done on the encapsulated components following the AEC Q101 procedure. After 1000 cycles of TCT, the components were taken out of the chamber, cross-sectioned, and prepared for microstructural observation. Both Pb92.5/Sn5/Ag2.5 and the two HTLF solder pastes had shown neither corner cracks nor delamination after 1000 cycles of TCT for both die-attach (die to leadframe) and clip-bonded (clip to die top) joints, shown in Fig. 4.

Both HTLF-1 and HTLF-2 are Sn-rich solders, while Pb92.5/Sn5/Ag2.5 have limited Sn (5wt%). As known, Sn dominates the interfacial IMC formation. Compared to high-Pb solder, HTLF-1 and HTLF-2 have shown thicker interfacial IMCs, which is expected because of the high Sn content.



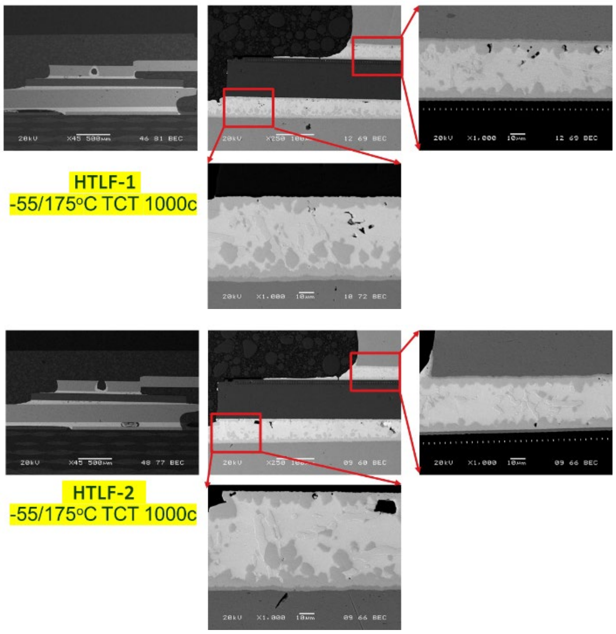


Fig. 4. Joint morphology of the encapsulated components after 1000 cycles of TCT (-55/175°C) from Pb92.5/Sn5/Ag2.5, HTLF-1, and HTLF-2.

F. RDS(on)

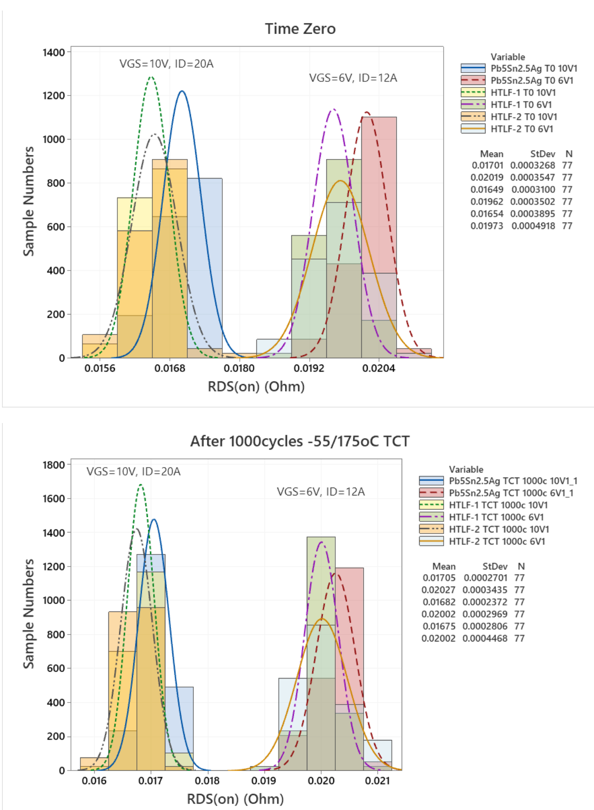


Fig. 5. RDS(on) distribution before and after 1000 cycles of TCT -55/175°C for the encapsulated components built with Pb92.5/Sn5/Ag2.5, HTLF-1, and HTLF-2.

RDS(on) of the components had also been measured before and after TCT (-55/175°C). Fig. 5 shows the RDS(on) distribution before and after 1000 cycles of TCT. Both HTLF-1 and HTLF-2 have similar RDS(on) values and are smaller than Pb92.5/Sn5/Ag2.5 before and after TCT, which indicates that both HTLF pastes outperform Pb92.5/Sn5/Ag2.5 in electrical performance. HTLF-1 has a distribution shape similar to Pb92.5/Sn5/Ag2.5, while HTLF-2 has the wider distribution range. So far, we did not know exactly the reason for the different RDS(on) distribution, and the current high-Pb process has been assumed to contribute to the difference. In this case, it seems HTLF-1 is more compatible to the current high-Pb process while HTLF-2 may need further optimization of the process to achieve the narrower distribution. It was also noticed that the difference of RDS(on) between HTLF pastes and Pb92.5/Sn5/Ag2.5 became less after 1000 cycles of TCT, as shown in Fig. 5.

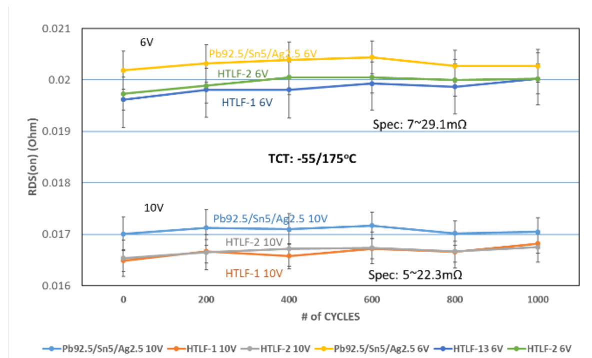


Fig. 6. RDS(on) of the encapsulated components for Pb92.5/Sn5/Ag2.5, HTLF-1, and HTLF-2.

In order to clarify the trend of RDS(on) change with TCT, Fig. 6 summarized the change of RDS(on) with TCT cycle numbers at the 200 cycles interval for both HTLF pastes and Pb92.5/Sn5/Ag2.5. First, both HTLF-1 and HTLF-2 clearly outperformed Pb92.5/Sn5/Ag2.5 in RDS(on) in the entire TCT. The results validate the design that the intrinsic lower electrical resistivity of Sn-based alloys than Pb improves performance. Second, HTLF-1 was shown to be slightly better than HTLF-2. The process optimization may help to reduce the difference between these two HTLF pastes. Third, the difference of RDS(on) between the HTLF pastes and Pb92.5/Sn5/Ag2.5 become smaller after 1000 cycles of TCT. After TCT, both HTLF pastes and Pb92.5/Sn5/Ag2.5 have no corner cracks or delamination from joint morphology as shown in Fig. 4. Therefore, the RDS(on) shift is possibly attributed to the solder joint microstructural evolution and the interfacial IMC growth.

IV. Conclusions

Two Sn-based HTLF solder pastes combining the merits of two constituent powders were prepared and tested as drop-in solutions to replace high-Pb solder pastes in power discrete applications. Both HTLF solder pastes (HTLF-1 and HTLF-2) can be successfully processed to build encapsulated components using the current high-Pb production process. Voiding and MSL performance are similar for both HTLF solder pastes and comparable to Pb92.5/Sn5/Ag2.5. Neither cracks nor delamination were observed in the joint cross-section morphology after 1000 cycles of TCT (-55/175°C). Both HTLF solder pastes substantially outperformed Pb92.5/Sn5/Ag2.5 in RDS(on) before and after TCT. The current results validated the new design; the two pastes developed on basis of the design (HTLF-1 and HTLT-2) have been successfully demonstrated in the production with the current high-Pb process although optimization may still be needed. The performance of the components with HTLF pastes is superior to that of Pb92.5/Sn5/Ag2.5 as was desired in the design.

In conclusion, HTLF-1 and HTLF-2 provided new drop-in options for replacing high-Pb in power discrete applications, with superior performance compared to high-Pb.

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