A Novel Design of High-Temperature Lead-Free Solders for Die-Attachment in Power Discrete Applications

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Abstract
Development of high-temperature lead-free (HTLF) solders to replace high-lead solders for die-attachment in power device applications is driven by (1) the harmful effects of lead to human health and the environment, and (2) the demand of the improved bonding materials serving under high-power density and high-junction temperatures, especially for wide-band-gap power devices. A novel design, based on a mixed solder powder paste technology—Durafuse™—has been developed to deliver a Sn-rich HTLF paste, presenting the merits of both constituent powders. The combination of the rigid, high-melting SnSbCuAgX and the ductile, low-temperature Sn-rich solder in one paste enables reflow at a relatively low temperature (barely above the liquidus temperature of the final joint composition) and maintains the joint strength above 15MPa in the temperature range between 270˚C and 295˚C. The sufficient high-temperature strength has demonstrated the capability of maintaining the joint integrity during subsequent multiple SMT reflows below the 270˚C peak temperature, regardless of the existence of a partial melting phase. Both X-ray inspection and cross-section microstructure have not shown any damage in the Si die or any noticeable cracks in the bonding joint, even after 3000 cycles of TCT (-40 to 150˚C). In summary, Durafuse™ HT, the novel design of the high-temperature lead-free pastes, has shown the feasibility as a drop-in solution to replace high-lead solders for die-attachment in power discrete applications.

Key words
high-temperature solders, lead-free, die-attach, power discrete

I. Introduction
Lead-free solders have been widely studied, and SnAg, SnCu, and SnAgCu have become the mainstream alternatives for the electronics industry. However, high-temperature lead-free (HTLF) solders, replacing conventional high-lead solders in die-attachment for power semiconductor devices, are still in the early stages of development. Die-attachment for power devices requires the usage of high-temperature solders to maintain the joint integrity between Si die and the metal leadframe/substrate in service. The major requirements for HTLF solder in die-attachment include (1) joint softening and a remelting 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 current high-lead soldering processes, (4) good thermal fatigue resistance, (5) comparable or improved electrical/thermal performance to high-lead solders, and (6) low cost. Increasing demands of wide-band-gap semiconductors (SiC/GaN) require new soldering materials to survive harsh conditions and provide enhanced electrical/thermal performance.

Currently, there are no matured drop-in HTLF solutions for power semiconductor die-attachment. Possible alternative solders have been extensively studied and summarized [1], including: (1) solder materials, i.e., AuSn/AuSi/AuGe, BiAg/BiAgX, BiCu/BiCuX, SnSbCuAg, and ZnAl, (2) interdiffusion bonding materials, i.e., Ag/nano-Ag sintering materials, and (3) transient liquid phase bonding (TLP bonding) materials (CuSn and AgIn). Fig. 1 has summarized the mechanical performance of a few die-attach materials from an ambient temperature to 300˚C. All lead-free candidates have shown stronger joint shear strength than the high-lead solders. Au-rich materials and ZnAl outperform all others LF alternatives, showing the bond shear strength above 50MPa at 250˚C. However, the high cost of Au-rich materials and the high reactivity of the ZnAl material restricted their application. BiAgX® was designed with a mixed powder paste technology [1,2], and contained a low- melting Sn-containing powder (melting temperature <230˚C), a high-melting BiAg/BiCu powder (melting temperature >262˚C), and a flux. The intrinsic thermal and electrical properties of Bi results in the inferior performance compared to its high-lead counterpart, although BiAgX® outperforms the high-lead solders in bond shear strength.

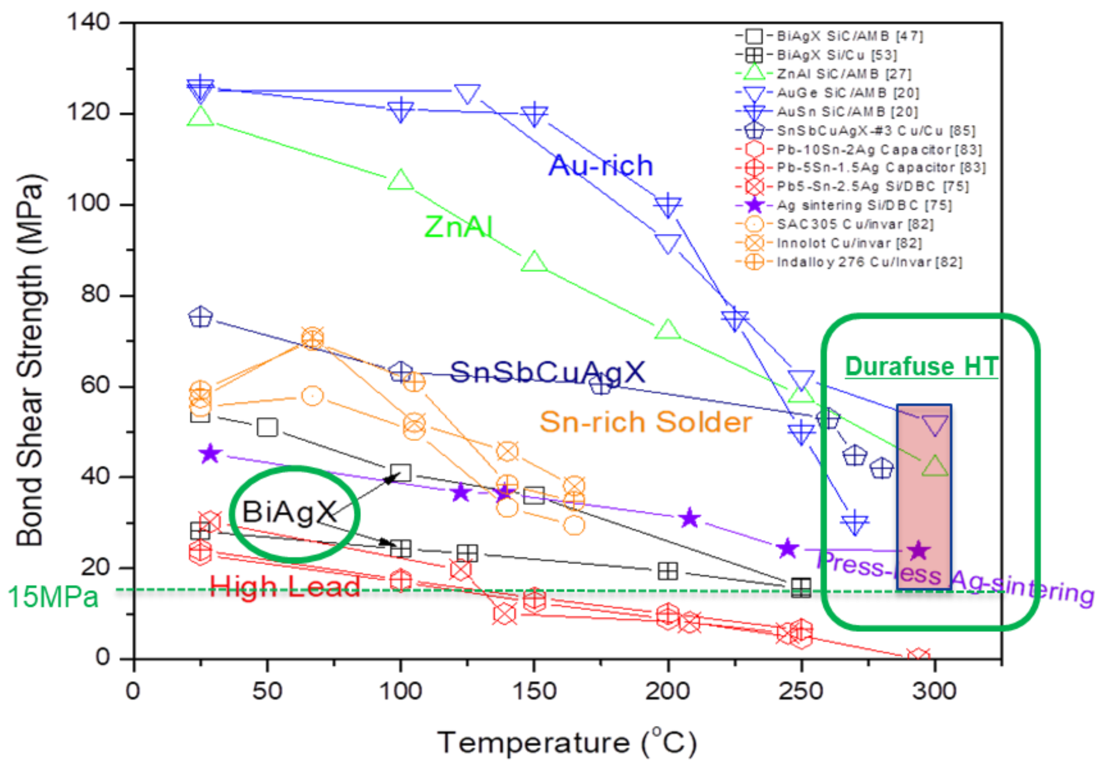


Fig. 1. Summary of Die-attach Bonding Materials [1].

SnSbCuAgX (solidus temperature >320˚C and liquidus temperature >360˚C) has shown good bond shear strength with the temperature range from ambient temperature up to 280˚C [1,3]. The thermal conductivity of SnSbCuAgX is around 34W/mK, which is superior to high-lead solders (27~32W/mK) [3]. However, SnSbCuAgX is rigid and needs a high reflow temperature because of the high liquidus temperature, which causes Si die damage in Si-Cu packages [3]. Sn-rich solders (SnAg/SnCu/SnAgCu) are ductile, and good in both thermal conductivity (40~60W/mK) and electrical resistivity (1.2~1.6x10^{-5} ohm-cm). In addition, Sn-rich solders have a lower melting temperature from around 217˚C to 230˚C. The mixed powder paste technology has been used to design a novel paste composed of (1) the high-temperature SnSbCuAgX, (2) the ductile and low-melting Sn-rich solder, and (3) the flux. The combination of both SnSbCuAgX and Sn-rich solder are expected to outperform the high-lead solders through their joint merits, namely, (1) maintaining high-temperature strength, (2) balancing rigidity and ductility, (3) lowering the reflow temperature, and (4) inheriting the thermal and electrical behaviors from both powders.

The appropriate ratio of two powders in the paste design will be the key to make it work. If the amount of low-melting ductile Sn-rich powder is too little, the rigidity of SnSbCuAgX may still break Si dies. Too much of the low-melting ductile Sn-rich powder might compromise the high-temperature bond shear strength. High-lead solders have been widely used in the industry with proven performance. They maintain the high-temperature shear strength of around 10MPa at 260˚C (see Fig.1), which allows the encapsulated packages to survive the subsequent SMT reflow without solder extrusion or delamination. Based on the guidance of DA5, the desired bond shear strength should be above 15MPa. Thus, the new pastes are designed to have the bond shear strength exceeding 15MPa at 260˚C and above, which mechanically outperforms high-lead solders under identical conditions by 50% more. The high-temperature bond shear strength is expected to help the bonding joint survive the subsequent SMT reflow as high-lead solders do.

II. Paste Design

SnSbCuAgX is rigid and has a higher melting temperature than traditional high-lead solders. The rigidity and hot reflow profile associated with higher melting temperatures may cause Si die damage in Si-Cu die-attach packages [3]. Lead-free SnAgCu solders have been widely used in electronics industry. SnAgCu solders have low-melting temperatures (217 to 220˚C) and are ductile. Combining both SnSbCuAgX and SnAgCu in one paste to form the joint may not only maintain the high-temperature mechanical performance, which was dominated by the high-temperature melting SnSbCuAgX, but also lower the processing temperature and enhance the ductility, contributed by the low-melting and ductile SnAgCu. In addition, both SnSbCuAgX and SnAgCu have better thermal conductivity and electrical resistivity than traditional high-lead solders; thus, the final joints from the mixed powder paste are expected to inherit both the electrical and thermal performances. The designed pastes have the product name "Durafuse™ HT".

The design had been validated on Si-Cu packages ($5x5mm^2x0.15mm$ Si on 0.55mm-thick Cu coupons) with three pastes, which were selected from combinations of two SnSbCuAgX powders and two SnAgCu powders [4]. The packages were reflowed in a customized vacuum chamber with a peak temperature of 360˚C for 60s. After 3000 cycles of TCT (-40/150˚C), no obvious joint damage or broken Si die were identified, although interfacial IMC growth and microstructural coarsening were seen [4].

After this concept-proof test, four new pastes have been designed with a wide range of ratios between two constituent powders. These new pastes are targeted at exploring the boundaries of this novel design and to study the impact of processing. One paste from the previous concept-proof test has also been included as the control. A total of five pastes, named 874-33-1~5, were included in the current study.

Differential scanning calorimetry (DSC) was used to characterize the thermal behavior of the five pastes. 873-33-1 was the control paste from the past concept-proof test. Two well-separated endothermal peaks (melting peaks) have been observed from all five pastes, which may indicate a "pause" between the first minor melting and the second major melting, as shown in Fig. 2.

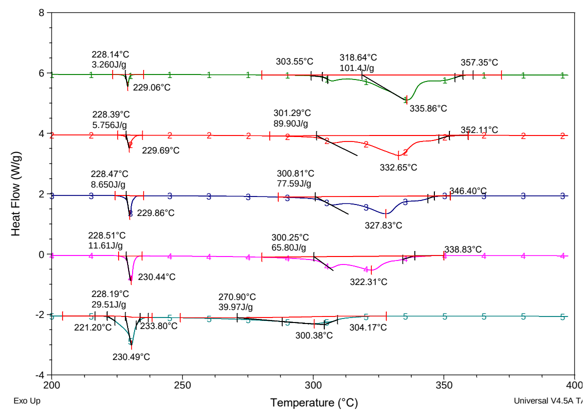


Fig. 2. DSC of the spheres reflowed from 874-33-1~5 pastes.

Table 1 summarizes the DSC data, including (1) the onset temperature, (2) the peak temperature, (3) the end temperature, and (4) the heat absorption from each melting peak. The first melting peak is similar for all five pastes, with the peak temperature around 229˚C. 874-33-1~4 have the similar onset melting temperature around 300˚C for the second melting peak, while 874-33-5 has the onset temperature dropping to around 270˚C. The heat absorption from each peak is paste dependent.

Table I. Data summary from DSC for 874-33-1~5

	Peak 1			Peak 2				Ratio
	Tonset 1 (oC)	Tp1 (oC)	Delta H1 (J/g)	Tonset 2 (oC)	Tp2(oC)	Tend2 (oC)	Delta H2 (J/g)	Delta H1/Delta H2
874-33-1	228.14	229.06	3.26	303.55	335.86	357.35	101.4	0.03
874-33-2	228.39	229.69	5.756	301.29	332.65	352.11	89.9	0.06
874-33-3	228.47	229.86	8.65	300.81	327.83	346.4	77.59	0.11
874-33-4	228.51	230.44	11.61	300.25	322.31	338.83	65.8	0.18
874-33-5	221.2	230.49	29.51	270.9	300.38	304.41	39.97	0.74

The ratio of heat absorption from the low-melting peak towards the high-melting peak (Delta H1/ Delta H2) for all five pastes ranges from 0.03 to 0.74. These numbers indicate the ratio of the low-melting phase relative to the high-melting phase. The higher the ratio, the more the low- melting phase is before major melting starts. For the current five pastes, 874-33-1 has the smallest portion of the liquid phase before major melting occurs above 300˚C (the onset of 2nd melting peak), while 874-33-5 has the largest liquid phase below 270˚C.

III. Bond Shear Strength

DSC has shown the "pause" between the two melting peaks. The bond shear strength in the temperature range between the melting peaks will further confirm the melting "pause." Fig. 3 has summarized the dependence of the bond shear strength from Cu-Cu assemblies ($3x3mm^2x0.5mm$ Cu die on Cu substrate) on the increasing testing temperature (up to 295˚C) for all five pastes.

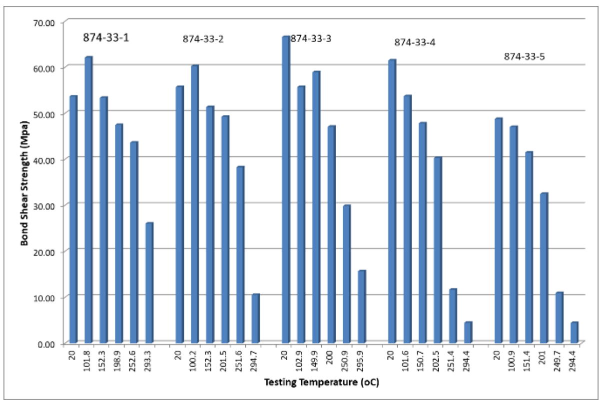


Fig. 3. Shear strength of the Cu-Cu joints formed with 874-33-1~5 pastes.

Keep in mind that die-attach components may need go through the SMT reflow multiple times (peak temperature from 230˚C to 270˚C). The high-temperature bond strength between 250˚C and 295˚C has been emphasized. Both 874-33-1 and 874-33-3 have shown the bond shear strength higher than 15MPa. 874-33-2 has the bond shear strength of around 10MPa at 295˚C although the bond shear strength was as high as 38MPa at 250˚C. 874-33-4 and 874-33-5 exhibited the low bond shear strength (5 to 12MPa) between 250˚C and 295˚C although their bond shear strength was above 30MPa below 200˚C.

Recall the design criteria of the bond shear strength >15MPa under elevated temperatures to maintain joint integrity. The focus was on the 874-33-3 paste although tests were conducted on all five pastes. The test data here on are exclusively from 874-33-3 paste if not specified.

IV. Temperature Cycling Test

Two different Si die sizes were used to build the test vehicles: $1.8x1.8mm^2x0.25mm$ TiNiAg-Si die and $4.2x2.4mm^2x0.1mm$ TiNiAg-Si die. In addition to the Si die size, two Cu leadframes, with different pad areas but the same thickness of 0.21mm, were used. The pastes were dispensed on the small pad of one Cu leadframe to bond the associated small Si die ($1.8x1.8mm^2$). For the large Si die ($4.2x2.4mm^2$), the pastes were printed with a 4mil thick stencil (100% open aperture) onto a large pad of another type Cu leadframe. After placing the Si die, the packages were reflowed in a BTU oven with the peak temperature of 340˚C for small die packages and 345˚C for large die packages. The reflow peak temperature is barely above the liquidus temperature for one of the tested solders (874-33-3).

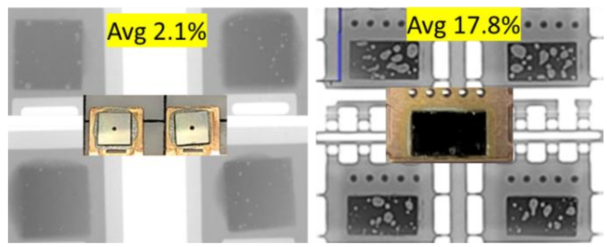
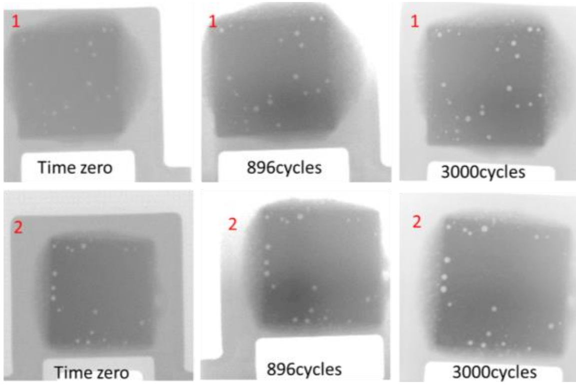


Fig. 4. Package and X-ray images. Left: $1.8x1.8mm^2x0.25mm$ Ti/Ni/Ag-Si die on Cu leadframe; Right: $4.2x2.4mm^2x0.1mm$ Ti/Ni/Ag-Si die on Cu leadframe.

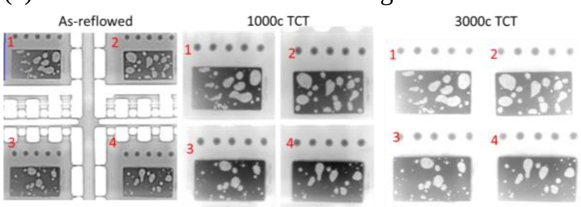
The testing vehicles and the associated X-ray inspection images are shown in Fig. 4. The small packages (Fig. 4, left) had good voiding performance, with an average as low as 2.1%. The large packages (Fig. 4, right) had an average voiding of 17.8%, which is higher than the industry requirement of below 15%. Additional work is being implemented to optimize the voiding.

The temperature cycling test (TCT) was carried out for both packages with a profile from -40 to 150˚C with 10min dwelling time and roughly 52min per cycle. Die shear was used to monitor the joint degradation on both packages. Small packages (0.25mm thick) showed the cracking inside Si die instead of joint rupture upon die shear. For thin and large die-attach assemblies, the shear blade skidded over the surface of Si die and could not catch the joint strength at all. Thus, the joint degradation had been monitored with both X-ray inspection and cross-section microstructure.

Fig. 5 shows the representative X-ray inspection images up to 3000 cycles TCT for both packages. Different from the high-lead solders, whose joint degradation was featured as the perimetric crack formation [1,5], 874-33-3 joints have shown little change along the perimeter for both packages.



(a) 1.8x1.8mm^{2}x0.25mm Ti/Ni/Ag-Si die on CuLF



(b) 4.2x2.4mm^{2}x0.1mm Ti/Ni/Ag-Si die on CuLF

Fig. 5. X-ray inspection of die-attach packages.

The test packages were then cross-sectioned, molded, ground, and polished to characterize the joint damage under TCT. Fig. 6 shows the joint morphology of both test packages. For small Si die packages, low voiding has been confirmed by the cross-section images. However, large voids were seen in large die-attach packages. Die-tilt has also been observed in both packages, where the bondline thickness (BLT) is thinner on one side. The small package shows the BLT between 20 to 40 microns while the large package shows the BLT from ~20 to 75 microns.

High-lead solder normally shows creep-fatigue cracks along the perimeter of the bonding joint after TCT [1,5]. Different from high-lead solders, 874-33-3 has shown neither clear solder cracks nor die cracks for either package type after 3000 cycles TCT. The previous concept-proof TCT test on 5x5mm^2 Si die on Cu substrate had revealed the same observation. Recall that 874-33-3 has a joint shear strength of more than 45MPa at 200˚C. The strong high-temperature bond shear strength of 874-33-3 is attributed to excellent creep resistance, which reduces the opportunity of crack initiation and growth driven by CTE-mismatch between Si die and CuLF.

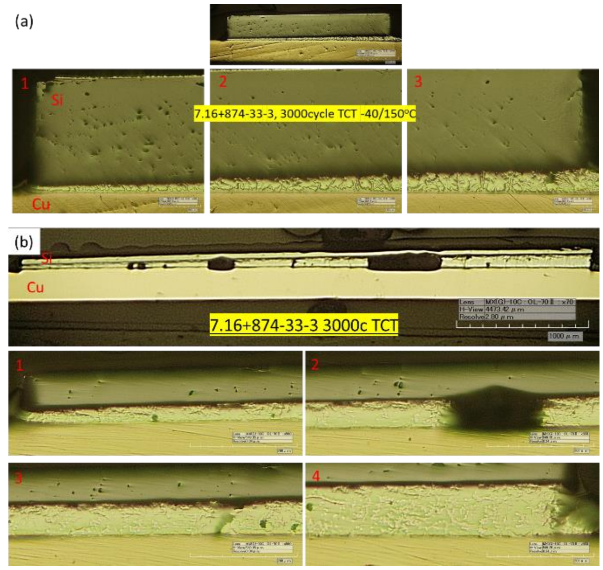


Fig. 6. Cross-section of Si-CuLF die-attach joints with 874-33-3 paste. (a) 1.8x1.8mm^{2}x0.25mm Ti/Ni/Ag-Si die on CuLF. Top: overview; 1: left corner; 2: middle; and 3: right corner of the joint. (b) 4.2x2.4mm^{2}x0.1mm Ti/Ni/Ag-Si die on CuLF. Top: overview; 1: left corner; 2: mid-left; 3: mid-right; and 4: right corner of the joint.

V. DISCUSSION

High-lead solders have high-melting temperatures (>280˚C), maintaining the joint integrity of the encapsulated components during the subsequent SMT reflow. Durafuse™ HT paste was designed to have good joint strength of >15MPa in the temperature range of the SMT reflow process (250˚C to 270˚C) even if a partial melting phase existed. Durafuse™ HT pastes, for example 874-33-1~5, have shown two well-separated melting peaks in DSC, indicating a "pause" of melting between 230˚C and 300˚C for 874-33-1~4 or between 230˚C and 270˚C for 874-33-5. One of the selected pastes, 874-33-3, has been successfully used to build a MOSFET-type power discrete, which has passed subsequent pre-conditioning tests (3x SMT reflow). This had confirmed the validity of the design idea that sufficient high-temperature strength will maintain the joint integrity even if partial melting exists in subsequent SMT reflows.

High-melting SnSbCuAgX solders were tried on die-attach packages and Si-die-rupture was observed after TCT or even after reflow [3]. The combination of the ductile low-melting Sn-rich solder powder and the high-melting SnSbCuAgX solder powder into one paste enables reflowing at a relatively low temperature and results in enough ductility to relieve the residual stress. The current test has demonstrated that one of the designs, 874-33-3, can be reflowed from 340˚C to 345˚C, which barely exceeds the liquidus temperature of the final joints. After reflow and the following 3000 cycles TCT, no damage in the Si die and solder joints were observed.

Durafuse™ HT pastes were designed to outperform high-lead solders in terms of joint reliability, and the electrical and thermal performances. The electrical resistivity of the 874-33-3 formulation was measured to be around 1.6~2.0x10^{-5}ohm-cm from cast cylinder samples. The thermal conductivity of 874-33-3 formulation from cast disks is around 36~40W/mK. Both thermal conductivity and electrical resistivity of 874-33-3 are confirmed better or at least comparable to high-lead solders.

Commonly, the encapsulated power discrete would generate higher internal stressing than the opened testing packages as the authors have presented in this paper. The authors are working with a beta site to test the selected paste (874-33-3) in the midst of a product feasibility run.

VI. Conclusion

A novel design of HTLF solder pastes (Durafuse™ HT) have demonstrated the success in die-attachment applications. The combination of the rigid high-temperature SnSbCuAgX alloys and the ductile low-temperature Sn-rich solders demonstrated the advantages both being reflowable at relatively low temperatures and having sufficient high-temperature joint strength. The sufficient high-temperature strength maintains the joint integrity in preconditioning tests even when a partial melting phase exists. In addition, the reflowed joints had survived 3000 cycles TCT without noticeable damage in either the Si die or bonding joints.

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