

# Transient Liquid Phase Sintering (TLPS) Conductive Adhesives for High Temperature Automotive Applications

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## ABSTRACT

Power electronics products such as inverters and converters involve the use of Thermal Interface Materials (TIMs) between high power packages and a heat exchanger for thermal management. Conventional TIMs such as thermal greases, gels, solders and phase change materials (PCMs) face challenges to meet the need of these products to operate reliably at much higher temperatures. This has driven the development of new TIMs such as Transient Liquid Phase Sintering (TLPS) Conductive Adhesives. TLPS adhesives have been developed for many potential applications due to various advantages like lead free, flux-less and particularly their low temperature processability, which enables the use of heat sensitive components in the design. With all these motivations, a project was launched and completed to assess TLPS adhesives as a unique TIM for high temperature automotive applications due to its high bulk thermal conductivity and metallic joint formation at interfaces.

This paper reports the evaluation of three different TLPS conductive adhesives with different formulations. All the TLPS adhesives contain lead-free eutectic SnBi fillers, together with other fillers with much higher melting point ( $T_m$ ) so as to process them using low temperature profiles. Different processing profiles were applied to process different TLPS adhesives. After processing, the assemblies could meet high temperature application requirements due to the shift of  $T_m$  of SnBi alloy from 139°C to a much higher value >200°C. Three different heat exchanger materials including bare Cu, Al and AlSiC with solder wettable surface finishes were assessed. X-ray was used to check void formation and Scanning Electron Microscopy (SEM) was conducted on the cross sections to study the quality of the whole metallurgical network. Die shear force was used to verify the joint strength. Thermal resistance measurement was carried out to verify thermal performance of TLPS assemblies. Thermal cycling test (-40 °C to +135 °C) had been performed to assess the reliability performance of the assemblies. TLPS samples built on Al and Cu substrates exhibited higher thermal resistance due to higher mis-match of coefficient of thermal expansion (CTE) with that of AlN, while TLPS samples assembled on AlSiC substrates were much more reliable and showed low thermal resistance throughout the thermal cycling test.

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## INTRODUCTION

Automotive power devices have stringent requirements on both thermal and electrical performance, particularly after long-term temperature and humidity exposures with high power on [1]. The temperature protection of the Si-based power die is at about 180°C maximal, with constant temperature at 150°C. Much higher operating temperature can be expected for SiC and GaN based power devices. Excellent electronic liquid cooling systems are thus needed to dissipate the heat generated and to be reliable with thermal cycling of -40 °C to 150 °C for a minimum of 1000 cycles [2]. In power electronics applications, the TIM between high power packages and a heat exchanger plays a key role in the cooling system [3]. The continual need to increase the performance of high power devices also requires improved TIM thermal performance and reliability.

Conventional TIMs such as thermal greases, gels, solders and PCMs are facing challenges to meet the stringent requirements of power electronics products. Adhesive dry-out, pump-out and structural fractures are some of the main concerns. This has led to the development of new TIMs and new applications of unique materials such as Transient Liquid Phase Sintering (TLPS) Conductive Adhesives. TLPS adhesives have been developed for many potential applications such as die attachment and PCB via filling. These TLPS materials have various advantages like lead free, flux-less and particularly low temperature processability, which enables the use of heat sensitive components in the design [4, 5].

TLPS conductive adhesive, the hybrid of conventional conductive adhesive and solder, is the best of both worlds. It consists of a polymer flux system and a metal system.

including metal fillers with high  $T_m$ , e.g. Cu or/and Ag and solder fillers with relatively lower  $T_m$  e.g. SnPb or Pb-free alloys. The solder reflow process first melts and coats contacting surfaces and the high  $T_m$  fillers to form a metal-polymer inter-penetrated network. This is followed by a heating process which causes the TLPS to sinter, where the solid metal powder particles e.g. Cu coexist with a liquid solder phase e.g. SnBi, and densification of the mixture takes place as the metals diffuse into one another [6]. The composition of solder is therefore changed over time with inter-diffusion, causing a  $T_m$  shift to higher values. This principle has been demonstrated successfully in materials joining in semiconductor device packaging [7, 8, 9, 10, 11, 12].

This work is the first to report the assessment of TLPS Conductive Adhesive as potential TIM for active liquid cooling heat exchangers in automotive environments. Three different TLPS conductive adhesives, with eutectic SnBi solder fillers, were processed using low temperature profiles and then evaluated in terms of void formation, metallurgy and adhesion, together with their thermal and reliability performance during thermal cycle test.

## EXPERIMENTAL METHODS

Three (3) different TLPS conductive adhesives, containing eutectic SnBi solder particles and other metal fillers with much higher  $T_m$  and proprietary formulations, were studied. TLPS adhesives were processed in a convection oven using different profiles. A Differential Scanning Calorimeter (DSC) was used to study the  $T_m$  shift of processed materials.

X-ray was used to check the void formation in the assemblies. Cross-sectioning and Scanning Electron Microscopy (SEM) were conducted to observe the quality of the metallurgical network. Energy-Dispersive X-ray spectroscopy (EDX) was used to detect composition changes of elements Sn, Bi, Cu and intermetallic compounds at different locations. Test coupons were made using 4mm × 4mm IGBT chips with Au backside metallization assembled onto Cu plates with Ni/Au plating. A Dage tester was used for die shear test. A 2mm × 2mm testing chip with Ni/Au backside metallization was used for shear testing.

Three different heat exchanger materials, including Al and AlSiC with solder wettable surface finishes as well as bare Cu all with coupon sizes of 12.7mm × 12.7mm, were assessed. These coupons were bonded to 12.7mm × 12.7mm Aluminum Nitride (AlN) ceramic substrates with Direct Bonded Aluminum (DBA) and Ni/Au surface finishes on both sides using these 3 TLPS adhesives. Total thermal resistivity measurements were carried out by a Laser Flash method to verify thermal performance of these assemblies. Thermal cycling testing (−40 °C to +135 °C) was performed to assess the reliability performance of the assemblies up to 2000 cycles.

## RESULTS AND DISCUSSION

### TLPS Conductive Adhesives Study

Three different TLPS conductive adhesives, namely TLPS-A, TLPS-B and TLPS-C, were acquired and assessed. They all contained eutectic SnBi solder particles, in addition to metal fillers with higher  $T_m$  e.g. Cu or/and Ag. Eutectic SnBi solder fillers were chosen so as to process these materials at low temperatures. The respective polymer flux resin systems in each TLPS material were different and proprietary. These materials possess thermal conductivity of typically greater than 20W/mK, which is considered quite high as compared with that of typical thermal greases, gels and PCMs, yet slightly lower than that of solder due to the existence of interpenetrated polymer. As compared to conventional solder flux, the proprietary polymer flux system in the TLPS adhesive generates no flux residue after processing and hence costly flux cleaning step can be eliminated.

Different TLPS materials can be processed using different profiles. Several processing profiles were recommended by datasheet provided by material supplier for different and even the same adhesive. Typically, the first step was to melt / reflow the SnBi solder alloys to coat contacting surfaces as well as all the Cu/Ag fillers to form a metallic-polymer interpenetration network, which have high thermal and electrical conductivities. An isothermal sintering step was then performed to facilitate inter-diffusion, mainly between Sn of solder and Cu or Ag, and to shift the  $T_m$  of solder alloy to a much higher value due to the change in alloy composition. In our study, a convection curing oven was used in the experiments. The melting of SnBi fillers was done by controlling the temperature ramp rate from room temperature to a maximum of 180 °C, followed by isothermal inter-diffusion at a constant 180 °C temperature.

Three different processing profiles, with different ramp rates, were applied to process the three TLPS adhesives. Profile-1 has the fastest ramp up from room temperature to a  $T_m$  of 139 °C. It reached 180 °C in less than 10mins. Profile-3 was the slowest, taking a total of 50min to reach 180 °C. Profile-2 was somewhere in between, taking around 15min to reach 180 °C. An isothermal step at 180 °C was then applied to complete the inter-diffusion or sintering for these three adhesives. Generally higher sintering temperatures, especially much higher than  $T_m$  of solder and longer duration, will promote faster and more inter-diffusion. However, shorter cycle time and lower energy consumption must be considered at the same time for practical applications.

DSC was used to verify the  $T_m$  shift of the SnBi alloys after processing. As an example, Figure 1 shows a typical DSC dynamic run curve of the adhesive TLPS-A before and after short processing. The first melting peak at about 140°C, represents the SnBi eutectic point, which then decreases in intensity after sintering. At the same time, the new melt peak at 203°C appeared and increased correspondingly. Further increase in temperature or/and duration of processing could

make the first peak fully diminished and the second peak reached its maximum, which means all SnBi eutectic alloys are transformed into an SnBi alloy with much lower Sn% i.e. higher Bi% relatively. The new alloy has a  $T_m$  of 203 °C. TLPS-B and TLPS-C adhesives showed similar findings as they contained the same SnBi solder fillers although the polymer resin systems were not the same.

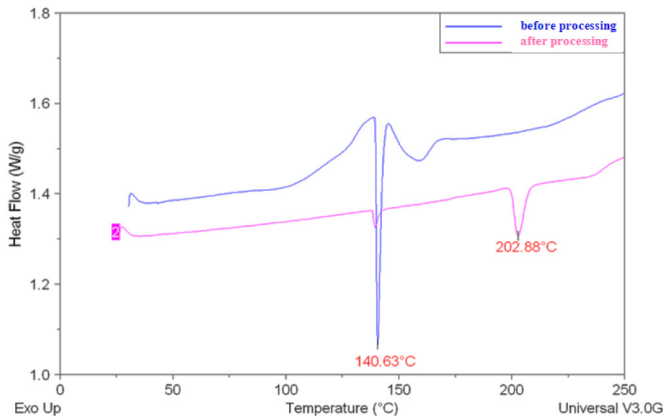


Figure 1. DSC dynamic run curves overlay of TLPS-A adhesive before and after processing

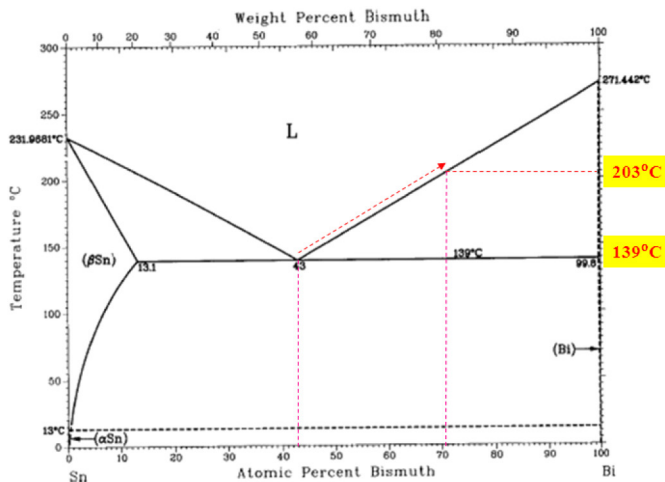


Figure 2. SnBi phase diagram

The unique shift of  $T_m$  exhibited by TLPS Adhesives can be easily explained by the SnBi Phase diagram, as shown by Figure 2. Eutectic SnBi melts at ~139 °C and molten SnBi then coats the adjacent contacting surfaces and the high  $T_m$  fillers e.g. Cu. Densification of the mixture takes place as the metals i.e. Sn and Cu diffuse into each other. Once the Sn concentration is diminished, and the relative Bi concentration increases, the new  $T_m$  will keep increasing up to 203 °C for the TLPS adhesives under the sintering condition applied in this study. Further increase in the sintering temperature will increase the  $T_m$  to even higher values. This confirms that TLPS adhesives can be processed at a lower temperature yet form a joint / assembly that can be used for high temperature applications. This is particularly important for products with

heat-sensitive components, and in addition provides savings from electricity power consumption and the elimination of flux residual cleaning.

## TLPS Adhesives Assembly Study

### Void Study by X-Ray

X-ray was used to check void formation of the processed assemblies upon treatment by different profiles. As shown in Figure 3, the TLPS-A material formed with no voids using all three processing profiles; the TLPS-B adhesive formed excessive voids under Profiles-1 and Profile-2, while almost no voids were observed under Profile-3; the TLPS-C adhesive formed excessive voids under Profile-1, few voids under Profile-2 and small yet consistent voids under Profile-3. A B-staging step at 90 °C was introduced to TLPS-C adhesive samples and the voids were reduced to very minimal number.

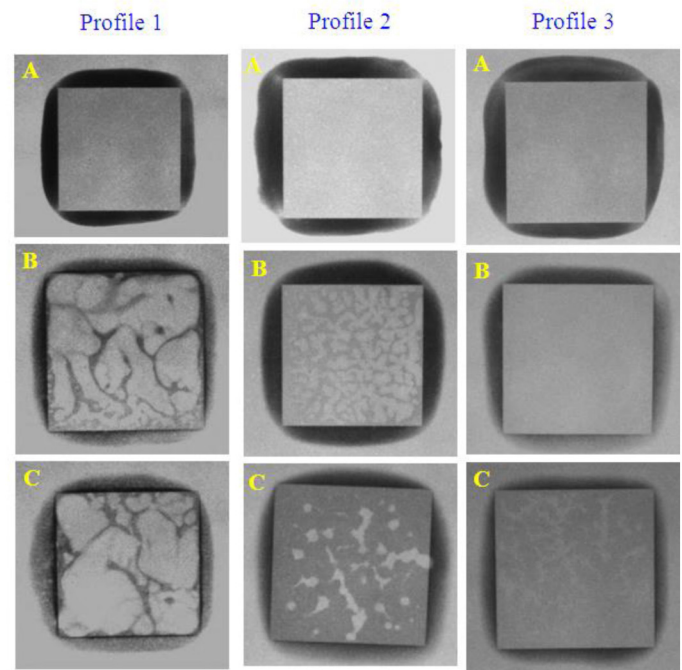


Figure 3. X-ray pictures of all the TLPS samples after processing by different profiles

All these findings showed that profiling was important and that it needed to be optimized for different TLPS adhesives due to their different formulations. This was especially critical for bigger joint areas. When using TLPS adhesives, the processing profile must be carefully studied to prevent the formation of large voids, which is very detrimental to the thermal and electrical performance of the joint, especially for automotive high power chips and packages.

### Metallurgical Study

Cross-sectioning and SEM analysis were then conducted to study the quality of metallurgical network after processing using different profiles. In adhesive paste for the TLPS adhesive is a polymer network with all the metal fillers