

Ag₃Sn IMC cluster suppression and heat transfer mechanism enhancement by controlling Sn content in Pb-based solder alloys

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ABSTRACT

Lead-based solder alloys remain widely used in power electronics due to their excellent wettability, high-temperature tolerance, and long-term mechanical stability. However, the formation of intermetallic compounds (IMCs), particularly Ag₃Sn, can adversely affect joint reliability by promoting brittleness and thermal fatigue. This study investigates the thermal behavior and heat dissipation characteristics of three PbSnAg solder compositions: PbSnAg-1 (medium Sn%), PbSnAg-2 (high Sn%), and PbSnAg-3 (low Sn%), using Differential Scanning Calorimetry (DSC) analysis. DSC results revealed that PbSnAg-2, with the highest Sn content, exhibited the narrowest melting range and lowest melting peak, indicating uniform phase transformation and reduced Ag₃Sn formation compared to PbSnAg-1 and PbSnAg-3. Thermal conductivity analysis further validated these trends, with PbSnAg-2 exhibiting the highest thermal conductivity at 206.6 W/m-K, approximately 73% and 66% higher than PbSnAg-1 and PbSnAg-3, respectively. These enhancements are attributed to improved Ag dispersion and suppressed IMC clustering, facilitated by higher Sn reactivity. Based on this experimental evidence, we can infer that the Sn content in the solder composition plays a crucial role in defining the melting behavior, IMC evolution, and heat dissipation efficiency. PbSnAg-2 demonstrates superior thermal stability, reduced IMC formation, and significantly enhanced thermal conductivity, making it a reliable choice for thermally demanding power electronic applications.

Keywords: Lead-Based Solder, Differential Scanning Calorimetry (DSC), Intermetallic Compound, Sn Reactivity, Thermal Conductivity, Mechanical Properties, Solder Joint Reliability, Phase Diagram, Power Electronics

1. INTRODUCTION

The continuous miniaturization of electronic devices coupled with increasing power densities has placed unprecedented demands on interconnection materials, particularly in high-reliability applications such as automotive power modules, aerospace electronics, and high-frequency communication systems (Ismail et al., 2018) (Arpilleda, 2023). Despite global environmental regulations restricting the use of lead in consumer electronics, lead-based solder alloys remain crucial in specialized high-temperature and high-power applications due to their exceptional combination of thermal stability, mechanical reliability, and economic viability (Said et al., 2022). These applications frequently operate under severe thermal and mechanical stresses, with junction temperatures often exceeding 200 °C during normal operation and power cycling (Tanaka et al., 2023). Under such conditions, the integrity of solder interconnections becomes crucial to the reliability and performance of the overall system.

The high-lead solders containing tin and silver (PbSnAg) have emerged as preferred materials for die-attach applications in power modules due to their superior wettability, appropriate melting ranges, and enhanced resistance to thermal fatigue compared to binary compositions (Zhang & Lee, 2020). The addition of Ag to Pb-Sn systems serves multiple functions: it enhances mechanical strength through solid solution strengthening and precipitation hardening mechanisms, improves electrical and thermal conductivity, and critically, acts as an effective inhibitor of interfacial intermetallic compound (IMC) growth during thermal aging (Li et al., 2023). However, the efficacy of these solders is highly dependent on their composition, with even minor variations in Sn and Ag content potentially resulting in significant differences in thermal behavior, mechanical properties, and long-term reliability (Cong et al., 2023).

The formation of IMCs within PbSnAg solder joints represents a double-edged sword. While some intermetallic formation is necessary for establishing robust metallurgical bonds at interfaces, excessive intermetallic growth,

particularly of brittle phases such as Ag₃Sn, can compromise joint integrity through several mechanisms: increased brittleness, reduced ductility, diminished thermal cycling resistance, and degraded thermal conductivity (Chen & Siow, 2021). This delicate balance becomes even more critical in electronic power applications where efficient heat dissipation is essential for preventing thermal runaway and ensuring long-term reliability. As highlighted by Cong *et al.* (2023), the thermal conductivity of solder joints can decrease by up to 40% when excessive IMCs form, creating significant thermal barriers that impede efficient heat transfer from semiconductor dies to heat sinks (Cong *et al.*, 2023).

Recent investigations into the Pb-Sn-Ag ternary system have advanced our understanding of the complex relationships among composition, microstructure, and properties in these specialized solders. Xie *et al.* (2015) demonstrated that Sn content plays a pivotal role in the formation and distribution of Ag₃Sn intermetallics, with higher Sn concentrations promoting more uniform silver dispersion throughout the solder matrix. Their work revealed that Sn content of 8-12 wt.% optimized the balance between adequate wetting characteristics and controlled intermetallic formation (Xie *et al.*, 2015). These findings were corroborated by Liu *et al.* (2009), who observed that excess Ag₃Sn formation in low-tin PbSnAg solders created preferential sites for crack initiation and propagation during thermal cycling, significantly reducing joint lifetime (Liu *et al.*, 2009).

The thermal behavior of PbSnAg solders has been extensively investigated using differential scanning calorimetry (DSC), which provides critical insights into phase transformation sequences, melting characteristics, and thermal stability (Ahmad *et al.*, 2024). Peng *et al.* (2020) established correlations between DSC thermograms and microstructural evolution in PbSnAg systems, demonstrating that the intensity and temperature range of exothermic peaks directly corresponded to the extent of intermetallic formation during solidification. Their research indicated that broader melting ranges typically resulted from more complex phase transformations and heterogeneous microstructures, which negatively impacted both mechanical properties and thermal performance (Peng *et al.*, 2020). Building on this work, Wernicki and Gu (2020) developed methodologies for extracting thermal conductivity data from DSC measurements, establishing direct relationships between thermal behavior and heat dissipation capabilities in complex solder systems (Wernicki & Gu, 2020).

The critical relationship between IMC formation and thermal conductivity in solder joints has been elucidated by several researchers. Yu *et al.* (2017) reported that the thermal conductivity of PbSnAg solders decreased proportionally with increasing volume fraction of Ag₃Sn intermetallics, with reductions of up to 35% observed in compositions with excessive silver content. This phenomenon was attributed to the intrinsically lower thermal conductivity of IMCs compared to the primary solder matrix, combined with increased phonon scattering at phase boundaries (Yu *et al.*, 2017). Zhou *et al.* (2020)

further refined this understanding by establishing that the distribution of intermetallics was as important as their volume fraction, with clustering of Ag₃Sn phases creating more significant thermal barriers than uniformly dispersed particles (Zhou *et al.*, 2020). Their work suggested that optimized Sn content could simultaneously enhance Ag distribution and suppress intermetallic clustering, leading to improved thermal performance.

The mechanical implications of intermetallic formation in PbSnAg solders have also received significant attention. Chuang *et al.* (2012) conducted comprehensive hardness test studies across a range of solder alloys, revealing that regions rich in Ag₃Sn exhibited substantially higher hardness but reduced elastic modulus compared to the surrounding matrix. These mechanical heterogeneities created stress concentration sites during thermal cycling, accelerating fatigue crack initiation and propagation (Chuang *et al.*, 2012). Complementary work by Hou *et al.* (2023) used synchrotron X-ray microtomography to visualize crack formation and propagation in thermally cycled solder joints, confirming that failures preferentially initiated at or near Ag₃Sn intermetallic clusters in compositions with poorly distributed silver (Hou *et al.*, 2023).

Despite these advances, systematic investigations correlating the composition of PbSnAg solders with their thermal behavior, intermetallic formation tendencies, and heat dissipation capabilities remain limited. Cong *et al.* (2023) highlighted this knowledge gap, noting that most studies focused either on mechanical reliability or thermal performance in isolation, with few examining the interconnected nature of these properties and their joint dependence on composition. Additionally, the specific influence of Sn content on Ag distribution and subsequent thermal conductivity in high-Pb solders has not been comprehensively characterized, despite its critical importance for power electronic applications (Cong *et al.*, 2023).

The present study addresses these knowledge gaps through a systematic DSC analysis of three distinct PbSnAg solder compositions: PbSnAg-1 (medium Sn%), PbSnAg-2 (high Sn%), and PbSnAg-3 (low Sn%). By examining their thermal profiles, phase transformation behaviors, and calculated thermal conductivities, we establish correlations between composition, intermetallic formation tendencies, and heat dissipation capabilities. These findings provide valuable guidance for optimizing solder formulations for high-temperature, high-reliability electronic applications where thermal management is critical to long-term performance and reliability.

2. METHODOLOGY

2.1. Thermal Characterization

All alloy compositions in this study are reported in weight percent (wt.%). The PbSnAg-1, PbSnAg-2, and PbSnAg-3 formulations differ primarily in their Sn concentration. Differential Scanning Calorimetry (DSC) was employed to evaluate the thermal behavior of these Pb-based solder

pastes—PbSnAg-1 (medium Sn%), PbSnAg-2 (high Sn%), and PbSnAg-3 (low Sn%)—to determine key thermal transitions, including melting characteristics and solidification responses. The analysis was conducted using the TA DSC Q2000 model, a high-precision thermal analysis instrument provided by Quantum Skynet Solution, which offers accurate measurement capabilities for phase transitions, heat flow, and specific heat capacity of materials under controlled temperature conditions. Each solder sample was carefully prepared and evenly spread within a Tzero pan, ensuring optimal thermal contact. The pan was then sealed using an aluminum hermetic lid with pressure applied via the Tzero Press. The sample mass was limited to 5–15 mg to minimize thermal lag.

The thermal testing was conducted over a range from 30 °C to 350 °C at a heating and cooling rate of 20 °C/min under a nitrogen gas flow rate of 50 mL/min. The DSC measurements provided the solidus and liquidus temperatures, as well as the H_{fus} , for each solder alloy. Exothermic peaks during cooling were analyzed to determine the formation of Ag_3Sn IMCs, while endothermic peaks during heating indicated their dissolution (Wernicki & Gu, 2020). These data are essential for understanding phase transitions and IMC behavior, which influence the thermal and mechanical reliability of the solder joints.

Table 1. Differential scanning calorimetry (DSC) Parameters

Parameter	TA DSC Q2000
Temperature Range	30 – 350 °C
Heating Rate	20 °C/min
Cooling Rate	20 °C/min
Temperature Program	Equilibrate, Ramp heating, Isothermal, Ramp cooling
Sample Mass	5-15 mg
Atmosphere	Nitrogen (50 mL/min)
Pan type	Tzero Pan with Tzero Hermetic Lid

2.2. Thermal Conductivity

The thermal conductivity (k) of each solder alloy was estimated using the DSC-derived enthalpy of fusion and thermal transition data. The following formula, adapted from Eid et al. (2024), was used:

$$k = \frac{H_{fus} \times v_m}{A \times \Delta T} \quad (1)$$

where the thermal conductivity, k , enthalpy of fusion, H_{fus} , molar volume, v_m , heating rate, A , and temperature difference between liquidus and solidus temperature, ΔT , were taken respectively.

The v_m was calculated based on the average density of the alloy and the molar mass of its constituent elements, using standard material data. The thermal conductivity results enabled comparison between PbSnAg-1, PbSnAg-2, and PbSnAg-3, reflecting their heat dissipation performance. This method correlates thermal behavior with material performance, offering insights into how IMC formation influences thermal conductivity and overall solder joint reliability (Eid et al., 2024).

3. RESULTS AND DISCUSSION

3.1. Differential Scanning Calorimetry (DSC) Analysis

The DSC analysis provides essential insights into the phase transformation behavior and melting characteristics of PbSnAg solder alloys, which are critical for high-temperature and power electronic applications. Figure 1 illustrates the DSC thermograms of the three lead-based solder compositions: (a) PbSnAg-1, (b) PbSnAg-2, and (c) PbSnAg-3. These thermograms capture the heat flow behavior as a function of temperature during the heating cycle from 30 °C to 350 °C and provide critical thermal parameters, including solidus temperature ($T_{solidus}$), liquidus temperature ($T_{liquidus}$), and melting range (ΔT), all of which are fundamental to understanding solder melting behavior, phase formation, and reflow reliability.

In Figure 1(a), the DSC profile of PbSnAg-1 reveals a solidus temperature of 259.8 °C and a liquidus temperature of 304.6 °C, with a broad endothermic melting peak centred around 304.2 °C, reflecting overlapping melting reactions involving multiple Pb–Sn–Ag phases, including the concurrent dissolution of Ag_3Sn and Sn-rich domains. This relatively wide melting range ($\Delta T \approx 44.8$ °C) suggests the coexistence of multiple phases during melting and solidification, including the early formation of Ag_3Sn intermetallic compounds. The presence of an exothermic crystallization peak near 192 °C further supports this, indicating that certain phases begin to solidify earlier than the bulk matrix. Such phase separation and sequential crystallization behavior point to non-equilibrium solidification pathways, which can influence final microstructure, mechanical stability, and ultimately, joint reliability. Such non-equilibrium solidification produces microstructural heterogeneity, where phases nucleate at different temperatures and grow at different rates. This creates metastable Ag_3Sn and Sn-rich regions with mismatched thermal expansion behavior, generating localized stress during thermal cycling. Uneven nucleation kinetics further accelerates IMC coarsening, increasing brittleness and reducing long-term joint reliability. These deviations from equilibrium phase behavior alter phase stability and disrupt uniform nucleation kinetics, resulting in metastable microstructures that are more susceptible to fatigue and degradation under repeated thermal loading (Henderson et al., 2023).

Figure 1(b) shows the thermogram for PbSnAg-2, which has a solidus temperature of 280.5 °C and a liquidus temperature of 291.2 °C, resulting in a narrower melting range of 10.7 °C. The sharp, well-defined endothermic peak

at 290.5 °C suggests a single-phase melting process with minimal intermetallic interference. This narrow melting interval is beneficial for reflow soldering applications, as it enables more consistent melting and solidification, reducing the risk of void formation and joint stress concentration (Zolhafizi & Azlina, 2019). The higher Sn content in PbSnAg-2 shifts its solidification path away from primary Ag₃Sn formation regions in the Pb–Sn–Ag phase diagram, contributing to a homogeneous microstructure.

Figure 1(c) presents the DSC curve for PbSnAg-3, which displays the highest melting temperatures, with solidus and liquidus temperatures of 309.9 °C and 338.6 °C, respectively, with an intermediate melting range of approximately 28.7 °C. This elevated melting behavior is primarily due to its low Sn content and high Pb content, shifting the alloy composition towards the Pb-rich end of the phase diagram. The dual endothermic peaks at 308.4 °C and 338.3 °C suggest a multi-phase melting process, possibly involving late-stage Sn melting and Ag₃Sn dissolution. This finding aligns with Manasijevic *et al.* (2020), as the observed behavior corresponds to alloys exhibiting segregated intermetallic and multi-stage phase transitions, which can hinder fine-pitch joint formation and affect thermally sensitive assemblies (Manasijevic *et al.*, 2020).

Overall, the thermograms in Figure 1 confirm that solder composition, particularly the Sn-to-Ag ratio, plays a critical role in governing the melting characteristics and thermal stability of PbSnAg alloys. Among the three, PbSnAg-2 exhibits the most desirable thermal behavior for reflow soldering, with a sharp melting transition, reduced IMC interference, and minimal compositional segregation. These properties are especially advantageous in power electronic packaging, where thermal uniformity and microstructural control are essential for reliable solder joint formation and long-term performance (Amli *et al.*, 2023).

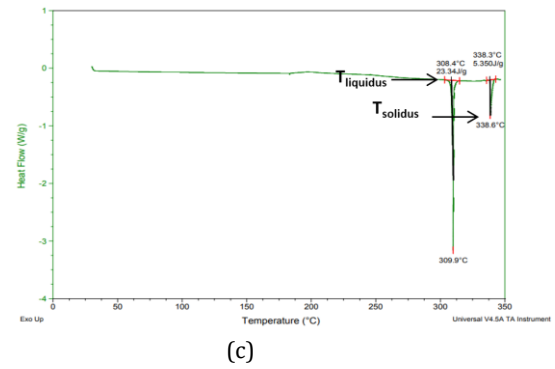
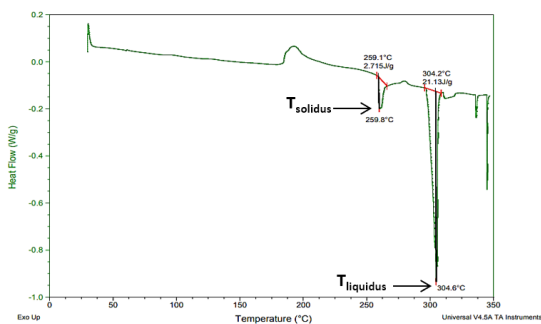


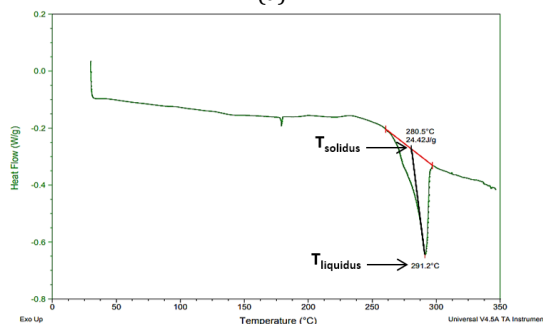
Figure 1. DSC Thermograms of (a) PbSnAg-1, (b) PbSnAg-2 and (c) PbSnAg-3 calculated density of State

3.2. Influence Of Ag₃Sn Formation On Mechanical properties Based On DSC And Phase Diagram Analysis

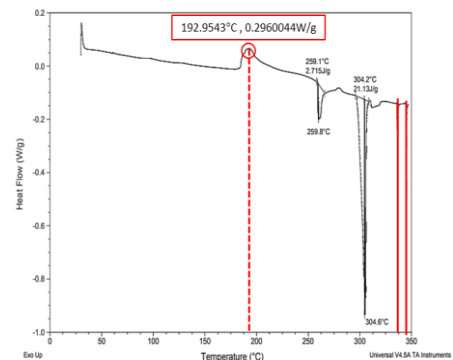
The differential scanning calorimetry (DSC) thermograms revealed significant differences in exothermic peak intensity among the three solder compositions, offering valuable insight into their intermetallic compound (IMC) formation behavior. As shown in the thermal curves in Figure 2(a), PbSnAg-1 exhibited a pronounced exothermic peak around 192 °C, indicating extensive Ag₃Sn(ε) phase formation during solidification. The formation of Ag₃Sn intermetallic can be further understood through the Ag–Sn phase diagram. The liquidus projection (Figure 2 (b), adapted from Du *et al.*, 2020) reveals that compositions with a higher Ag-to-Sn ratio, such as PbSnAg-1, lie within the region where primary Ag₃Sn phases are likely to form (Du *et al.*, 2020). This is consistent with the intense DSC exothermic response and explains the higher volume fraction of Ag₃Sn observed in PbSnAg-1. These IMCs typically nucleate as needle-like or plate-like structures, which introduce microstructural heterogeneity and act as stress concentration zones under mechanical loading. Such structures are especially susceptible to failure under thermal and mechanical cycling. Electron Backscatter Diffraction (EBSD) analysis has revealed that Ag₃Sn tends to form crystallographic orientations that facilitate crack propagation along shear planes, which in turn reduces fracture resistance (Stuart I. , 2018). This suggests that regions enriched with coarse Ag₃Sn clusters would exhibit lower effective hardness and modulus, as such IMCs act as brittle stress concentrators. Although mechanical properties were not directly measured in this study, this interpretation aligns with reported nanoindentation behavior of Ag₃Sn-rich microstructures.



(a)



(b)



(a)

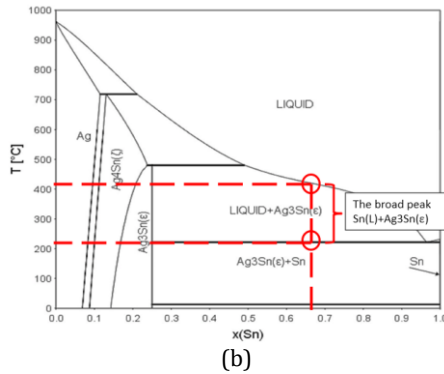


Figure 2. (a) illustrates from DSC thermograph the two-phase crystallization region of Pb and Ag₃Sn (ε), with a peak around 192 °C, (b) adapted from Du et al., (2020), shows a broad endothermic peak corresponding to the Sn(L) + Ag₃Sn (ε) region, spanning approximately from 230 °C to 420 °C.

In contrast, PbSnAg-2 exhibited a significantly weaker exothermic peak near 202 °C, suggesting greatly reduced Ag₃Sn formation. This composition benefits from a more favourable silver-to-tin ratio, which supports the uniform distribution of Ag in the Pb-rich matrix rather than its segregation into discrete IMC clusters. The isopleth section of the Pb–Sn phase diagram at constant Pb content (Figure 3b) confirms this, showing that increasing Sn shifts the solidification path away from Ag₃Sn-rich regions, thus suppressing primary intermetallic formation. Figure 3(c) shows that PbSnAg-3 presents an intermediate case.

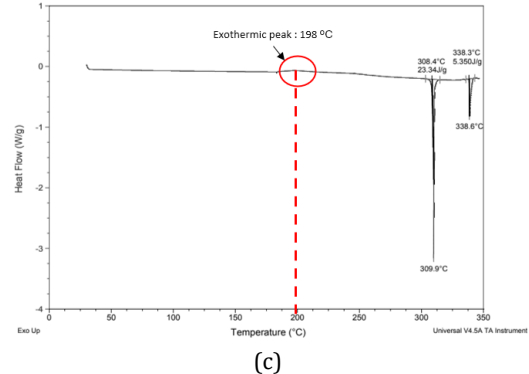
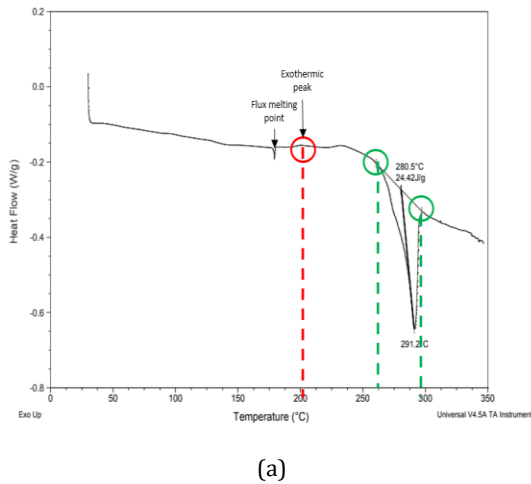


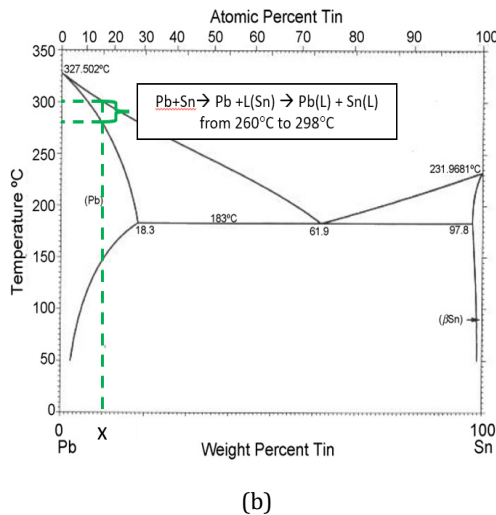
Figure 3. (a) shows the Pb + Ag₃Sn (ε) two-phase crystallization region with a peak around 202 °C. The broad and low-intensity peak indicates minimal formation of the Ag₃Sn (ε) phase. 3(b) presents the isopleth section of the Pb–Sn binary phase diagram, confirming that an increase in Sn content shifts the solidification path away from Ag₃Sn-rich regions. This shift suppresses primary intermetallic formation, following the sequence Pb + Sn → Pb + L(Sn) → Pb(L) + Sn(L), occurring between 260 °C and 298 °C. 3(c) displays the exothermic peak for PbSnAg-3, showing the Pb + Ag₃Sn (ε) two-phase crystallization region at approximately 198 °C. The broad and low peak further supports the minimal formation of the Ag₃Sn (ε) phase.

Beyond static strength, IMC morphology plays a crucial role in fatigue and creep behavior. He et al. (2021) demonstrated that compositions with high Ag₃Sn content had reduced thermal fatigue resistance due to preferential crack initiation at IMC boundaries. Their accelerated thermal cycling experiments showed that solder joints with minimal intermetallic clustering, like those of PbSnAg-2, exhibited up to three times longer fatigue life compared to IMC-rich compositions such as PbSnAg-1 (He et al., 2021).

These insights reveal that the superior mechanical behavior of PbSnAg-2 is rooted in its microstructural optimization. While intermetallic compounds such as Ag₃Sn can enhance mechanical strength through precipitation hardening, excessive and clustered IMC formation leads to embrittlement and increased fracture vulnerability. PbSnAg-2 effectively balances silver's strengthening role with tin's ability to distribute Ag uniformly, thereby enhancing both strength and ductility, which are critical factors for high-reliability solder joints in power electronic devices (Li et al., 2020).

In conclusion, the strategic balance of tin and silver in PbSnAg-2 promotes a refined and controlled IMC morphology, resulting in mechanically robust joints with enhanced resistance to thermal fatigue. These findings demonstrate that increasing silver content alone does not guarantee improved mechanical performance; rather, performance gains depend critically on achieving a microstructurally optimized distribution of Ag-containing phases. Integration of phase diagram interpretation with DSC analysis provides a predictive framework for designing solder alloys tailored to specific mechanical and thermal requirements.

The observed IMC evolution can be mechanistically attributed to the influence of Sn on the solidification pathway of the Pb–Sn–Ag system. Higher Sn content



increases Ag solubility in the molten alloy, delaying Ag segregation and suppressing the formation of coarse Ag₃Sn plates. As a result, Ag remains more uniformly distributed throughout the melt, leading to the development of fine, dispersed Ag₃Sn particles during cooling and producing a more homogeneous and stable solder matrix.

3.3. Thermal Conductivity And Heat Dissipation Performance

Thermal conductivity is a critical parameter in determining the efficiency of heat dissipation in power electronic packaging, particularly in high-temperature environments where thermal gradients can cause severe reliability issues. Solder joints with higher thermal conductivity can more effectively transfer heat away from active components, minimizing thermally-induced stresses and reducing the likelihood of crack initiation and propagation (Ismail *et al.*, 2024). In this study, the thermal conductivities of three PbSnAg solder alloys were calculated based on heat capacity values obtained through Differential Scanning Calorimetry (DSC) using Equation (1). The calculated thermal conductivity values are presented in Fig. 2, revealing significant differences among the three compositions.

PbSnAg-2 demonstrated the highest thermal conductivity at 206.6 W/m·K, which is 276.4% higher than PbSnAg-1 (54.9 W/m·K) and 194.8% higher than PbSnAg-3 (70.1 W/m·K). These remarkable improvements can be attributed to the balanced composition of tin and silver in PbSnAg-2. The presence of high Sn optimizes microstructural homogeneity and reduces the formation of Ag₃Sn intermetallic compounds (IMCs), which are known to disrupt phonon transport due to their distinct crystallographic boundaries and phase interfaces. IMC–matrix interfaces introduce sudden changes in lattice structure and bonding strength, causing phonons to scatter or reflect. Larger Ag₃Sn clusters increase the frequency of these scattering events and reduce thermal conductivity, whereas finer IMC dispersion minimizes interfacial disruptions and enables more efficient phonon propagation. These disruptions scatter phonons, thereby increasing thermal resistance. By limiting Ag₃Sn formation, phonon scattering is minimized, promoting more efficient thermal conduction across the solder matrix. Studies by Hsiang, Chen and Su *et al.* (2021) have confirmed that tin content within the range of 8–12% enhances the formation of continuous conduction paths in solder matrices by limiting IMC clustering and improving solidification uniformity (Hsiang *et al.*, 2021).

In contrast, PbSnAg-1, with a lower Sn content and higher Ag, showed significantly diminished thermal conductivity. The enhanced formation of Ag₃Sn IMCs, validated by phase transformation peaks in DSC thermograms, leads to microstructural heterogeneity. Ag₃Sn particles, while mechanically reinforcing, act as scattering sites for thermal carriers, thereby increasing thermal resistance (Zhou *et al.*, 2020). Similarly, PbSnAg-3 suffers from low tin content, limiting matrix continuity and inhibiting the development of thermally efficient pathways. The increased Pb content also contributes to higher melting temperatures and a

wider phase distribution, both of which negatively affect thermal performance (Li *et al.*, 2019).

The variations in thermal conductivity determined using Eq. (1) are summarized in Figure 4, which graphically compares the three compositions. The figure highlights the superior performance of PbSnAg-2, not only in terms of raw conductivity values but also in terms of consistency, as represented by lower error margins. These results are consistent with findings by Chen and Siow (2021), who emphasized the correlation between uniform microstructural morphology and improved heat transfer in Pb-rich solders (Chen & Siow, 2021). This improvement in thermal conductivity is consistent with this mechanism. Coarse Ag₃Sn clusters introduce numerous IMC–matrix interfaces that scatter heat-carrying phonons due to abrupt differences in atomic mass, bonding stiffness, and lattice structure. When Sn promotes a finer and more uniform IMC distribution, phonon scattering is reduced, and heat flow proceeds more efficiently through continuous Pb–Sn metallic pathways. Thus, Sn simultaneously suppresses Ag₃Sn clustering and enhances thermal conductivity.

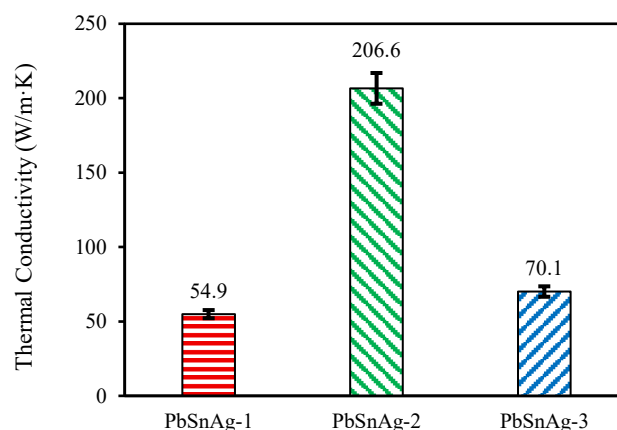


Figure 4. Thermal conductivity for three different Solder compositions

4. CONCLUSION

This study conducted a comprehensive thermal analysis of three lead-based solder alloys (PbSnAg-1, PbSnAg-2, and PbSnAg-3) using Differential Scanning Calorimetry (DSC) and thermal conductivity estimation to evaluate their suitability for power electronic applications. The experiments were performed using solder-only samples, ensuring that the thermal responses captured were purely intrinsic to the alloy compositions, without interference from substrate effects or environmental variables.

The DSC results revealed significant variation in melting behavior across the three solder types. PbSnAg-2, with the highest Sn content, exhibited the narrowest melting range and lowest melting temperature of 10.7°C and 312.9°C, respectively, which are preferred for enhancing reflow performance and minimizing thermal stress. In contrast, PbSnAg-1 and PbSnAg-3 demonstrated broader melting ranges and higher onset temperatures, indicating more complex phase transformations and less favorable wetting behavior. Intermetallic compound (IMC) formation,

particularly of Ag₃Sn, was also strongly influenced by Sn content. PbSnAg-2 showed a weaker exothermic peak during cooling, indicating lower Ag₃Sn formation, which supports a more ductile and thermally stable microstructure. Conversely, PbSnAg-1 and PbSnAg-3, with lower Sn content, exhibited stronger exothermic peaks, suggesting more extensive IMC formation and a higher risk of brittleness and thermal fatigue.

Thermal conductivity analysis further reinforced these findings, with PbSnAg-2 achieving the highest thermal conductivity at 206.6 W/m·K, approximately 73% higher

than PbSnAg-1 and 66% higher than PbSnAg-3. This enhanced heat dissipation capability is attributed to the higher Sn content, which promotes better Ag dispersion, reduces IMC clustering, and enables a more continuous conductive pathway within the solder matrix. These characteristics are especially critical for power electronics, where efficient thermal management directly correlates with device reliability and operational longevity. The findings suggest that PbSnAg-2 solder paste provides the optimal combination of thermal stability, controlled IMC formation, and high thermal conductivity, making it a strong candidate for high-reliability power semiconductor packaging applications.

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