Exploring Effective Thermal Conductivity and Thermal Resistance of Conductive Film Adhesive Bondline for High Power Density Applications

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Abstract

Silver filled epoxy film adhesives are widely used in electronic device assembly due to its dual functions in bonding different parts and facilitating heat transfer in electronic devices. The thermal properties of a film adhesive product are often provided in a form of intrinsic bulk thermal conductivity. However, when assessing the thermal performance of a conductive adhesive within a bonded assembly, the observed value might not be equivalent to the bulk property of a free-standing cured sample. In this paper, we use “sandwich” method enabled by laser flash to investigate the effective thermal resistance of a newly developed conductive film adhesive in an assembly that simulates the electronic device packaging. The assembly was prepared under different processing conditions such as bondline thicknesses and bonding pressures. The effects of bonding conditions and adherends on the thermal performance of this material will be discussed. This provides people with valuable insights on device packaging, material selection and design validation.

Key words

Electronic packaging, thermal management, adhesives, thermal interfacial materials

I. Introduction

Electrically conductive assembly films represent a class of materials offering robust adhesion and efficient electrical/thermal conductivity for circuit board materials, metal backplanes, and heat sinks with a uniform bondline [1, 2]. The rapid advancement of electronics, particularly in aerospace applications, has triggered the development of high thermally conductive assembly films capable of matching the heightened performance requirements of circuit boards that generate substantial heat.

However, the thermal performance of a functional film adhesive is often provided in a form of intrinsic bulk thermal conductivity. In practical applications, the effective thermal conductivity of the bondline emerges as a critical consideration, surpassing the intrinsic thermal properties of the adhesive material [3]. This is primarily attributed to two key factors: firstly, the significant divergence in contact thermal resistance and conductivity between adherents compared to the free-standing cured sample, owing to the diverse substrate materials encountered across various application scenarios; and secondly, the varying processing conditions such as cure pressure and bondline thickness, which exert notable influences on the effective thermal conductivity.

In this study, we scrutinize the effective thermal resistance and conductivity of a novel conductive film adhesive within a bonded assembly utilizing a three-layer "sandwich" methodology facilitated by laser flash. The "sandwich" samples (**Fig. 1**) serve to mimic the structure of electronic device packaging and are subjected to diverse bondline thicknesses and pressure conditions during curing. This approach yields significant insights into optimizing the assembly of electronic devices to maximize the performance of the assembly film adhesive. Additionally, the evaluation

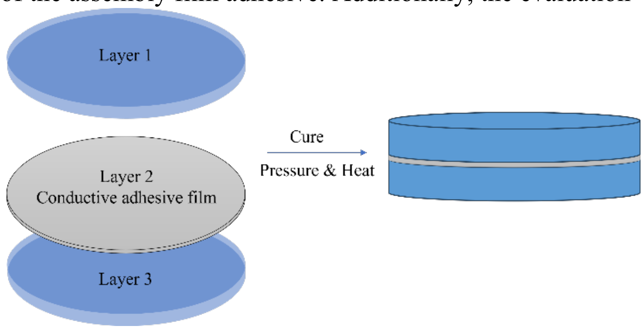

Fig. 1. Trilayer test set-up for laser flash measurements

of coefficient of thermal expansion (CTE) mismatch enables a comparative assessment between mechanical effects and thermal performance.

II. Materials and Methodology

Conductive assembly film adhesive:

Different from conductive die attach film (CDAF), which is within micrometer thickness and used to bond die within mm^2 size to provide adhesion and conductivity, the assebmly film (**Fig. 2**) is usually used for second level assembly. In a typical scenario, highly-complex printed circuit board (with a dimension of in^2) is mounted to a heat sink to effectively dissipate heat with an conductive assebmly film adhesive. The complexity and sensitivity of a PCB board limit the curing condition of assembly films preferably under 150°C, where sintering effect is unlikely to happen to yield high thermal conductivity. Most of the current conductive assembly films in the market provide a thermal conductivity from 0.9 to 7 W/mK depending on the formulation [4]. In this study, we use an adhesive film under deveopemnt with 20 W/mK as an example to prove the concept. **Table I** listed the kep properties of the film adhesive chosen in this study.

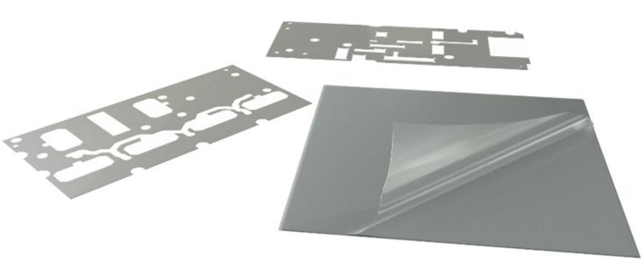

Fig. 2 Assembly film adhesives

Table I Film adhesive product chosen for the evaluation.

Properties	**Specifications**
Thickness	4, 6 and 8 mil (±0.5 mil)
Adhesion, Al/Al, 25°C	1500-1600 psi
Storage Modulus, DMA, 25°C	5 Gpa
Thermal conductivity, 25°C	20-25 W/mK
Electrical conductivity, 25°C	4.0-5.0 × 10^{-5} Ω·cm
Composition	Epoxy, silver fillers
Cure Schedule	150°C, 1hr (5-60 psi)

Substrate layers:

Three substrate materials were chosen as indicated in **Table II**.

Table II Substrates used as top and bottom layers.

Disk	Thickness, mm	Density, g/cm^3	Diameter, mm	Contact angle
Al_2O_3	0.26 ± 0.008	3.77	12	40° ± 4.0
Cu	1.03 ± 0.007	8.94	12	86° ± 1.0
Al	0.95 ± 0.005	2.71	12	64° ± 1.4

Methodology and sample preparation:

Trilayer laser flash:

Netzsch laser flash LFA 467 equipment was used to evaluate the in-package thermal performance of the chosen film adhesive. The test method was based on trilayer laser flash principles [3]. With two sets of assembly using the materials described above: Al_2O_3-ECF-Cu and Al-ECF-Al. A set of 3×3 full factorial experiments was designed as below:

Table III Design of experiments

Assembly	Factors	Levels	Response
Al_2O_3-ECF-Cu	Pressure	10, 40 and 60 psi	Thermal resistance
	Bondline thickness	4, 6 and 8 mil	
Al-ECF-Al	Pressure	10, 40 and 60 psi	Thermal resistance
	Bondline thickness	4, 6 and 8 mil	

The R_{tot} (total thermal resistance, mm^2-K/W) was calculated based on the λ_{eff} (effective thermal conductivity, W/mK) from laser flash and Δx (bondline measured after cure, mm):

$$R_{tot} = \frac{\Delta x}{\lambda_{eff}}$$

Each group contains at least 3 samples, and the average was calculated as the final result.

Sample preparation:

Adhesive films were punched into round samples with 12 mm diameter for later use. The exact thickness of each sample was measured in mm for 5 times with a thickness gauge and the average was calculated. Substrate disks were cleaned with isopropanol and pre-heated at 50°C on a hot plate. Samples then were assembled as in **Fig. 1** on the hot plate under 10 psi for 3min for better pre-tack. Curing schedule was set to 150°C for 1hr. Weight was placed on top of the samples during curing to create various pressures. After curing, the total thickness of the assembly was measured and subtracted by the substrate materials to get the bondline thickness after cure for later R_{tot} calculations.

Adhesion:

Adhesion of film adhesive with different thicknesses were evaluated in a form of lap shear strength. Lap shear panels made of Chromate etched aluminum panels (101.6mm X 25.4mm X 1.62mm) were assembled to measure the film's adhesion strength. Samples of film adhesives measuring 12.7 mm X 25.4 mm were cured between two aluminum (Al) panels to create a ½" long bonding area. The film adhesives were cured at 150°C for 1 hour. The lap shear strength tests were conducted with Instron 5900R. See **Fig. 4** for details on test specimen and instrument.

Thermal conductivity measurement of the free-standing samples:

Netzsch laser flash LFA 467 equipment was used to evaluate the thermal conductivity of free-standing film adhesive samples based on the specific heat and thermal diffusivity of the freestanding film samples measured. Adhesives were firstly hot laminated into ~0.5mm thick films and cured between Teflon films under 10, 40 and 60 psi under 150°C for 1 hr. After cure, samples were die cut into 12.7mm diameter round sample on a hot plate and cooled down to room temperature. The density, thickness and dimensions of each sample were accurately measured before test. Each group contains at least 3 samples, and the average was calculated as the final result.

II. Results and discussion

A. Bondline thickness change under various curing pressures

The control of bondline thickness is essential for high-power devices. Film adhesives instead of paste adhesives are able to assure reproducible thicknesses and void-free bondline provided uniform pressure and temperature are applied during curing [5]. Fibers that were used in some film adhesives contribute to adhesive flow control to some extent [6]. However, this function can be substituted with a film adhesive that has a higher filler loading such as the film adhesive used in this study. The investigation of the bondline thickness change during curing under various pressures, as summarized in **Fig. 3**, serves as a valuable indicator for this topic.

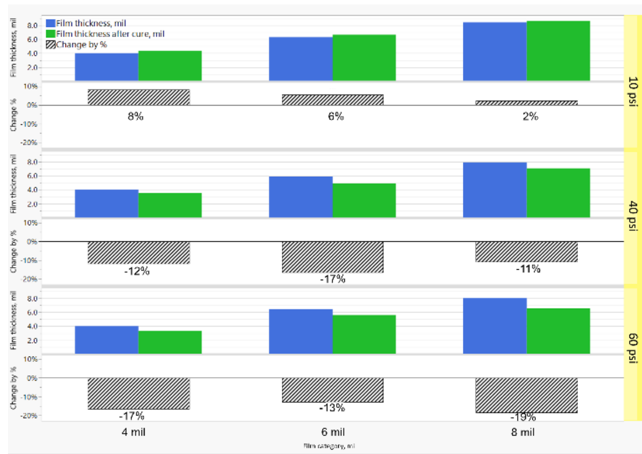

Fig. 3 Bondline thickness change after cure under different pressures

Thickness change was rarely observed under 10 psi. Slight increase may indicate expanded network structure during cure under mild pressure applied. As pressure increases to 40 and 60 psi, a decrease was observed from -11% to -19% (0.01mm to 0.04mm) in thickness but no obvious difference between the two pressures. And there is no discernible pattern showing that films of different thicknesses exhibit varying sensitivity to a particular applied pressure.

B. Lap shear strength of film adhesives with different thicknesses

Lap shear strength is one of the best indicators of the bonding strength of adhesives (**Fig. 4**).

(a) Test Specimen | (b) Instron 5900R

Fig. 4 Lap shear specimen and Instron 5900R

Before delving into the discussion of effective conductivity and interfacial resistance influenced by various thicknesses of interfacial material and processing pressures, it is crucial to investigate the impact of thickness on adhesion. This exploration is essential for comprehensively assessing the overall performance of the functional film adhesive utilized in this study.

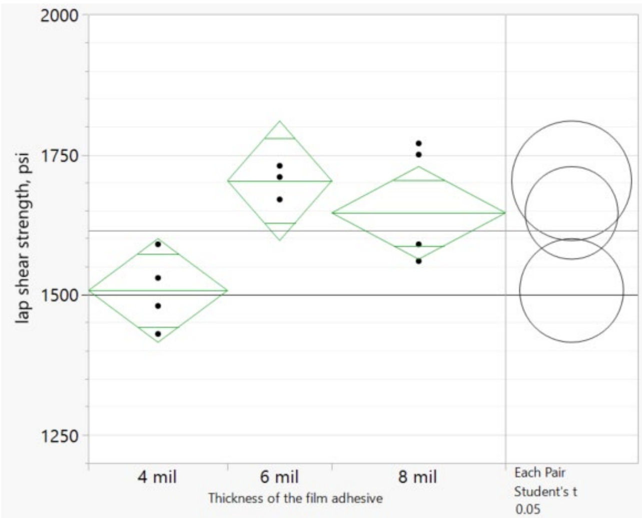

Fig. 5 Lap shear strength of the conductive film adhesive with different thicknesses

Fig. 5 summarized the results of the lap shear strength of ECF with 4-8 mil thicknesses in a form of One-way ANOVA and Student's t to analyze the difference between population means. The 4, 6, and 8 mil ECF samples exhibit average lap shear strength of 1500 psi, 1700 psi, and 1650 psi, respectively. Result from Prob > F is less than 0.05 indicating that there is difference between at least two of the means. Student's t analysis further confirmed the difference of adhesion between 4 mil ECF vs 6 mil & 8 mil. There is no significant difference between 6 and 8 mil ECF in adhesion.

C. Bondline effective thermal conductivity and thermal resistance

Thermal conductivity is one of the most important properties of conductive adhesives that help to ensure the performance and reliability of the electronic devices and other applications where good heat dissipation is needed.

In this paper, the thermal performance (z-axis) of the freestanding film adhesive cured under various pressures was firstly evaluated (**Table IV,** each value is an average of > 3 samples).

Table IV Thermal conductivity (through-plane, λ_z) at 25°C of the free-standing film adhesive cured under various pressures.

ID	Sample thickness	λ_z, W/m-K 10 psi	λ_z, W/m-K 40 psi	λ_z, W/m-K 60 psi
ECF	0.5mm	20.8	22.0	25.1

As shown in **Table IV**, the thermal conductivity of the film adhesive increased by ~21%, as the applied curing pressure elevated from 10 to 60 psi, with the curing temperature held constant at 150°C for the same duration of 1 hour. Similar observations were seen and discussed from some conductive pastes where assumptions were made regarding the change in particle-particle contact resistance between silver fillers [7].

Laser Fash tests on the trilayer test specimen were conducted. Effective thermal conductivities and thermal resistances across bondline are shown in **Table V**.

Table V Effective thermal conductivity and thermal resistance of ECF in-package.

Assembly	Film thickness. (before cure)	λ_{eff}, W/m-K	R_{tot}, mm^2-K/W	Cure pressure, psi
Al_2O_3-ECF-Cu	4 mil	0.19	58.8	10
Al_2O_3-ECF-Cu		0.25	35.4	40
Al_2O_3-ECF-Cu		0.22	37.9	60
Al_2O_3-ECF-Cu	6 mil	0.42	41.5	10
Al_2O_3-ECF-Cu		0.52	24.1	40
Al_2O_3-ECF-Cu		0.89	18.3	60
Al_2O_3-ECF-Cu	8 mil	0.84	30.3	10
Al_2O_3-ECF-Cu		1.9	9.7	40
Al_2O_3-ECF-Cu		1.6	10.5	60
Al-ECF-Al	4 mil	0.64	21.4	10
Al-ECF-Al		2.2	2.9	40
Al-ECF-Al		2.7	2.1	60
Al-ECF-Al	6 mil	1.4	11.2	10
Al-ECF-Al		6.5	1.5	40
Al-ECF-Al		9.0	1.3	60
Al-ECF-Al	8 mil	3.2	6.3	10
Al-ECF-Al		7.2	1.2	60

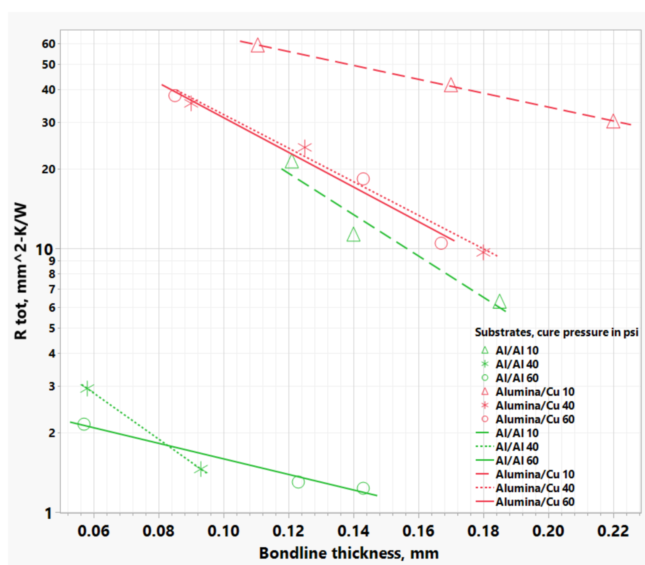

Fig. 6 Total thermal resistance vs. bondline thickness (after cure)

Fig. 6 summarizes the total thermal resistance vs bondline thickness. Each data point is the average of more than 3 replicates.

Theoretically, R_{tot} and bondline gap Δx are directly proportional, meaning as the bondline thickness is increasing, the total thermal resistance should increase as well. The intercept can be used to calculate the contact thermal resistance R_{con}, which is part of the total thermal resistance. But as seen from the graph, the R_{tot} decreased when bondline thickness increases indicating that in practice, thicker bondlines can accommodate better to surface topography and thus may reduce interfacial resistance.

The overall thermal resistance in Al_2O_3-ECF-Cu is much higher than Al-ECF-Al due to the surface roughness of the substrate material chosen, especially Al_2O_3 (see **Table II**). For example, under 60 psi, the total thermal resistance is only 1.2 mm^2-K/W in Al-ECF-Al vs. 10.5 mm^2-K/W in Al_2O_3-ECF-Cu for an 8-mil film sample. Compared to Al and Cu, Al_2O_3 used in this study has the roughest finish resulting in an obvious higher contact resistance, which was also observed during pre-tack step in sample preparation.

What is common from the two groups of assembly is that when pressure was increased from 10 psi to 40-60 psi, the total thermal resistance dropped significantly, 35.5%-65% in Al_2O_3-ECF-Cu depending on the thickness of the film used. This drop can go up to 90% in Al-ECF-Al. But the thermal performance between 40 and 60 psi is similar to each other from the fitting curve in the graph for both Al-ECF-Al & Al_2O_3-ECF-Cu assembly indicating that the performance (R_{tot} and λ_{eff}) was not much improved with further increased applied pressure from 40 to 60 psi.

From the current design, an effective thermal conductivity of up to 9 W/mK could be achieved, coupled with a thermal resistance of 1.3 mm^2-K/W. With the prospect of employing superior substrate materials, there is a strong likelihood of achieving even greater performance enhancements.

III. Conclusion

In summary, the investigation in this study evaluated the impact of varied applied pressures and film adhesive thicknesses on the effective thermal performance of electrically conductive assembly film adhesives in a three-layer assembly. The results indicate that by adjusting pressure in a certain range, the total thermal resistance can be improved significantly. Thicker film adhesive may reduce thermal resistance in practice. Some properties of substrate materials chosen to use in an assembly can have a significant impact on the effective thermal performance, such as surface roughness. Therefore, further studies on substrate surface metallization or treatment would be desirable to enhance the performance of the adhesive film in packaging applications.

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References

[1] Y. Zhao, D. Katze, J. Wood, B. Tolla and H. Yun, "High Temperature and High Reliability Performance of Electrically Conductive Film Adhesives for RF Grounding Applications," *International Symposium on Microelectronics,* vol. 2019, no. 1, pp. 000360-000363, 2019.

[2] W. Zhang, Y. Zhao, Z. Liu and S. Cheng, "An Evaluation on the Mechanical and Conductive Performance of Electrically Conductive Film Adhesives with Glass Fabric Carriers," *Journal of Microelectronics and Electronic Packaging,* vol. 20, no. 3, p. 101–106, 2023.

[3] R. C. Campbell, S. E. Smith and R. L. Dietz, "MEASUREMENTS OF ADHESIVE BONDLINE EFFECTIVE THERMAL CONDUCTIVITY AND THERMAL RESISTANCE USING THE LASER FLASH METHOD," in *Fifteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, San Diego, 1999.

[4] J. J. Licari and D. W. Swanson, "Chapter 3 - Chemistry, Formulation, and Properties of Adhesives," in *Adhesives Technology for Electronic Applications*, Elsevier, 2011, pp. 75-141.

[5] J. J. Licari and D. W. Swanson, "Reliability," in *Adhesives technology for electronic applications: materials, processing, reliability*, William Andrew, 2011, pp. 347-391.

[6] F. C. Cambell, "Chapter 8 – Adhesive Bonding and Integrally Cocured Structure: A Way to Reduce Assembly Costs through Parts Integration," in *Manufacturing Processes for Advanced Composites*, Elsevier, 2004, pp. 241-301.

[7] D. Lu, Q. K. Tong and C. P. Wong, "Conductivity Mechanisms of Isotropic Conductive Adhesives (ICA's)," *IEEE TRANSACTIONS ON ELECTRONICS PACKAGING MANUFACTURING,* vol. 22, no. 3, pp. 223-227, 1999.