Liquid Dispensed Thermal Materials for High Volume Manufacturing

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ABSTRACT

Industry 4.0, autonomous vehicles and 5G connectivity are driving a new Internet of Things (IoT) revolution. Assembly materials like thermal interface materials (TIMs) need to be selected keeping in mind both performance as well as economics viability. With higher volumes of various device designs, automated manufacturing and adaptable materials are also critical factors is the price-performance equation. Uniquely, liquid dispensed thermal interface materials (TIMs) are an optimal approach to address this convergence of high performance and cost-competitive manufacturing. Adaptable attributes – such as curable or non-reactive – make liquid TIM materials well-suited for a variety of applications. This paper presents the basic science behind liquid TIMs identifies key TIM characteristics needed to design and manufacture reliably and efficiently, and illustrates the relationship between material properties, performance and manufacturing compatibility. Fundamental differences between solid, pad-like materials and unfilled liquids will be highlighted.

INTRODUCTION

One key challenge in designing reliable electronic assemblies is ensuring the efficient dissipation of heat generated by the components. Components, when operating, produce varying degrees of heat, and this can reduce functional efficiency, performance reliability and the assembly lifetime. Therefore, thermal interface materials (TIMs) have become critical elements of electronic design in order to transfer and dissipate heat [1,2]. While thermally conductive gaskets and pads have been on the market since the 1980s, today's increased power densities, miniaturized devices and higher performance expectations have made thermal management a more integral part of the product design phase. [3, 4].

Modern TIMs are available in a variety of delivery formats with a wide range of properties. For certain applications, the fastest growing product segment is liquid dispensed thermal interface materials. Thermally conductive liquid TIMs offer not only better thermal performance and reliability, but allow streamlined manufacturing through automation and inventory consolidation.

This work aims to enhance general understanding of TIMs, discuss the basic structure and properties and detail the differences between pre-formed gaskets and non-conducting liquids.

THERMAL INTERFACE MATERIALS

Thermally conductive polymeric materials or thermal interface materials (TIMs) typically comprise of a polymer matrix within which thermally conductive particles have been dispersed. The term *thermally conductive* is, of course, relative. To give some perspective and as a measure of comparison, Table 1 shows some typical thermal conductivity values for various types of materials.

Table 1

Material	Thermal Conductivity ($W\text{-}m^{-1}\text{-}K^{-1}$)
Air	0.026
Typical Elastomers	0.1-0.2
Ceramics	2 - 300
Metals	100 - 1000
Graphite, Graphene, CNTs, Diamond	50 - 1000
Thermal Interface Materials	1-10

The objective of thermally conductive materials is to transfer heat away from the heat-generating device; eliminating any air gaps (voids) at the interface is essential to ensuring the most efficient pathway. As the table shows, the thermal conductivity of air is two to three orders of magnitude lower than that of typical TIMs. Heat transfer is improved significantly by eliminating this resistance to heat flow.

While thermal conductivity is one aspect of a material’s thermal performance - *conformability and wetting* of surfaces are also critical for success. The rheology of TIMs is the other essential component of a material’s thermal performance and ability to minimize assembly stress. The interface between surfaces has gaps on two different length scales. The first is small-scale roughness (Fig 1) – typically O (1 μm) – from which air is eliminated by flow and wetting by the interface material, while the bulk bond line can be O (1mm) needing higher thermal conductivity.

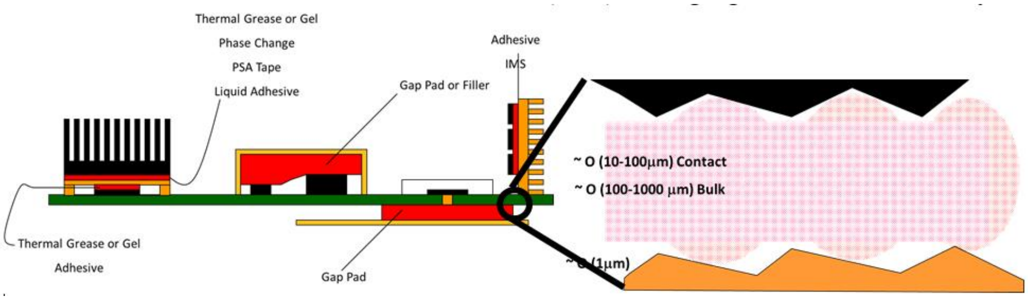


Fig. 1 – Thermal interfaces and thermal interface materials (TIMs)

The key properties of thermal interface materials, which affect the final performance, are thermal conductivity, rheology, yield stress and size of the particulates added to the material.

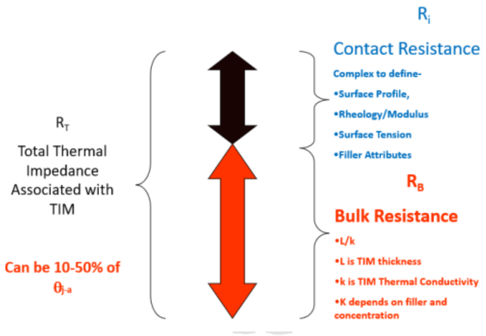


Fig. 2 – Thermal resistance of the TIM

LIQUID DISPENSED TIMs

Thermally conductive TIMs come as solid preforms or gaskets, as well as liquid mediums. Aside from the format, a primary difference between the two is the conformability of the material, which in turn may lead to better thermal performance depending on the application. Better wettability means liquid TIMs with lower thermal conductivity often perform better than higher conductivity pads/solids. In addition, stress during assembly is lower as liquids are easier to compress.

	Gap Pad - Solid	Gap Filler - Liquid
Thermal Conductivity	2	1.8
Thermal Resistance*	3.03	2.05

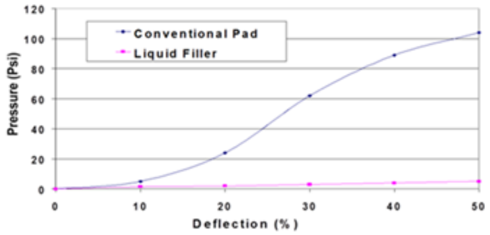


Fig. 3 – Comparing thermal and mechanical performance of pads and liquid TIMs

While improvement in thermal performance with liquid TIMs is an advantage, another significant benefit is the ability to automate TIM deposition. Advantages include: (1) optimized material usage in application, (2) quality control and repeatability and, (3) reduced inventory complexity due to fewer parts. Of course, there is a start-up cost associated with moving to automated TIM application, as dispensing equipment must be procured. Simple analysis of the program size and run rate can determine the return-on-investment (ROI). In general, most practical applications realize equipment investment ROI in less than two years, and sometimes in as little as a few months.

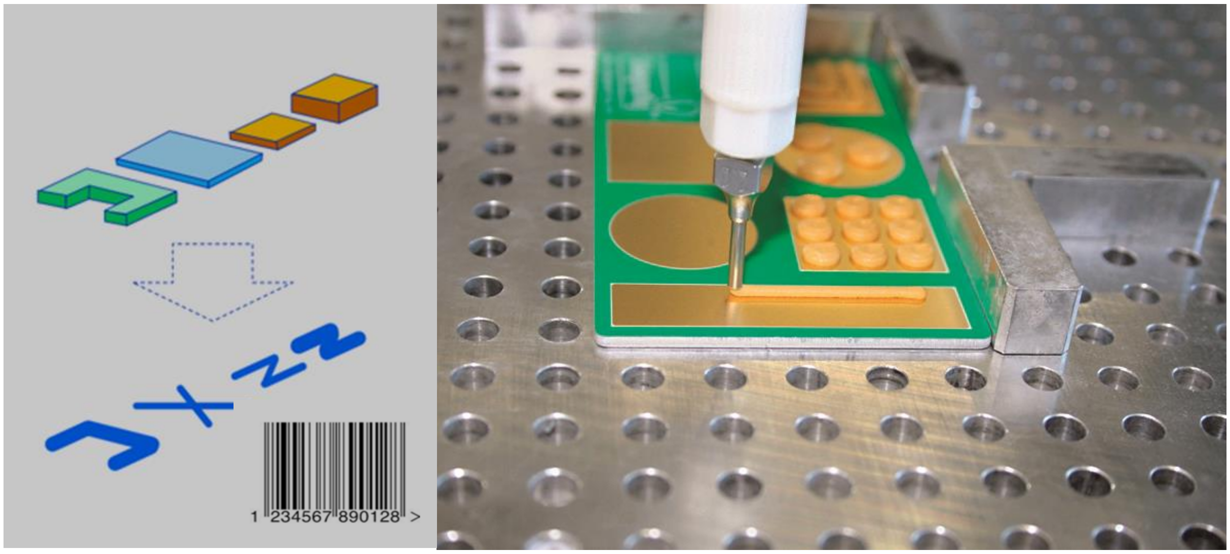


Fig. 4 - Inventory simplification and improved quality with Liquid TIMs

LIQUID TIMs TECHNOLOGY

The thermal conductivity of a polymeric material filled with thermally conductive fillers is a function of the thermal conductivity of the filler and the polymer. In addition, the increasing proportion of filler increases thermal conductivity [5-8]. Finally, the aspect ratio of the particles is central to determining the thermal conductivity value of thermally conductive polymers.

As seen in Fig 5, heat travels in serial and parallel pathways through polymer (slow heat transfer) and filler (fast heat transfer). As the filler fraction increases, so does thermal conductivity. Adding thermal filler also increases the viscosity of the TIM (Fig. 5).

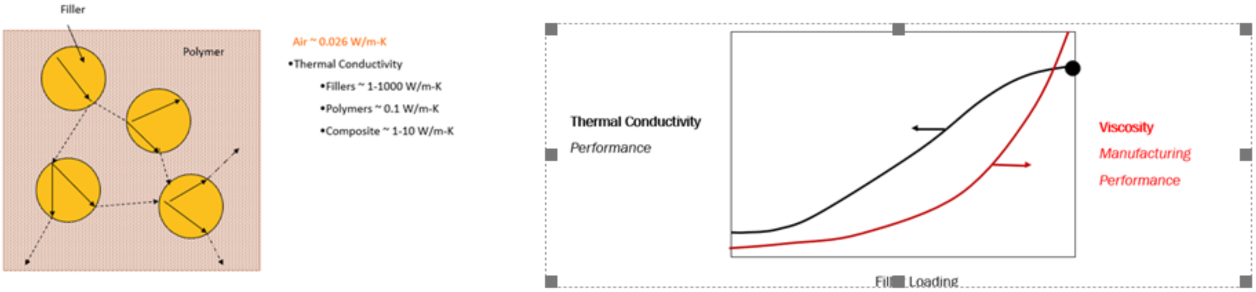


Fig. 5 – Conductivity and Viscosity dependence on Filler Loading

One model for thermal conductivity that has been widely used is the Nielsen model [7, 8], which reproduces the basic behavior of filled polymer composites.

$$\frac{k_c}{k_p} = \frac{1 + AB\phi}{1 - B\psi\phi}$$

Where,
k_c is composite thermal conductivity
k_p is polymer thermal conductivity
k_f is filler thermal conductivity
□ is filler content
A is a function of particle geometry

Other models are also available and have been reviewed recently for increasing sophistication and applicability [8].
Several models are available [9-16] for viscosity of dispersions from the very dilute to highly concentrated, that predict the behavior seen in Fig 5 Here, □ is the viscosity of the dispersion, □$_0$ is the viscosity of the polymer and□□$_r$ is the relative viscosity of the dispersion.

$$\eta_r = \eta/\eta_0 = 1 + 2.5\,\phi \quad \textit{Einstein}$$

$$\eta_r = \frac{\eta}{\eta_0} = \frac{9}{8}\left[\frac{\left(\phi/\phi_m\right)^{1/3}}{1-\left(\phi/\phi_m\right)^{1/3}}\right] : \textit{Frankel \& Acrivos}$$

$$\eta_r = 1 + 2.5\phi + 10.05\phi^2 + A\exp(B\phi) : Thomas$$

$$\log \eta_r = \frac{5}{2}\left(\frac{\phi}{1-K\phi}\right) : \textit{Mooney}$$

$$\eta_r = \left(\frac{1}{1-\phi/A}\right)^2 : \textit{Kitano, et.al.}$$

In general, the models above are related to the “zero” shear viscosity. For liquid TIMs, viscosity is a function of shear rate and, therefore, plays a pivotal role in manufacturing. While the TIM in a container is closer to the “zero shear” viscosity, the shear rate goes up during flow with a reduction in viscosity. These pastes behave as shear thinning liquids with an associated “yield stress” that needs to be overcome to deform the pastes. Several excellent reviews are available documenting the rheology of suspensions [9, 11, 17].

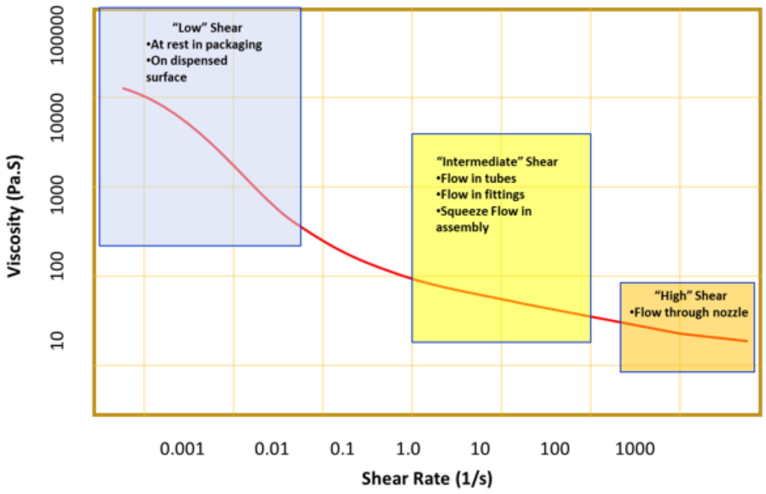


Fig. 6 – Rheology variation with shear rate – key to manufacturing

An increase in viscosity can reduce wetting and increase contact resistance and presents more processing challenges. For the best performance and manufacturability, it is important to focus on application needs and settle on the best combination of rheology and thermal conductivity.

One final important point is the bond line limitation, which is dependent upon the particle size distribution in the TIM. While thinner bond lines are achievable with liquid TIMs, they typically are limited to a minimum of 2-3x the particle size in the TIM.

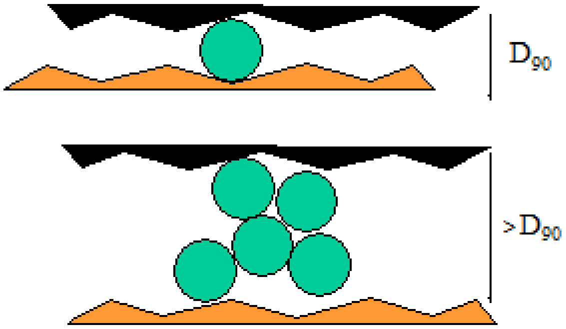


Fig. 7 – Bond line limitations

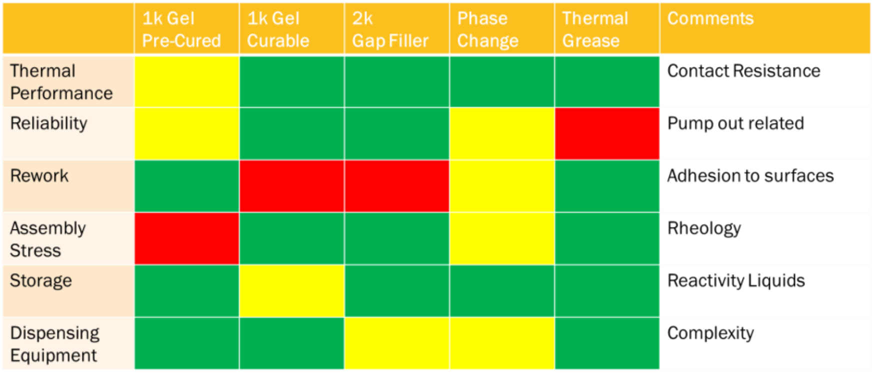
Liquid TIMs are available in various formats and should be evaluated and selected according to its relative suitability in an application. Liquid TIM formats include:
Thermal Greases: These are relatively lower viscosity polymer liquids that have been loaded with thermally conductive particulates. Greases are thermoplastic, meaning they will deform continuously under external stresses without limit.

Thermal Pastes or One-part (1K) Pre-cured Gels: These are relatively higher viscosity materials with higher molecular weight and a linear or branched polymer matrix. This gives them a certain rheological stability and some elastic properties. Pastes and gels are thermoplastic like greases.

Curable/Reactive Liquids – Two-part (2K) or 1K Gap Fillers/Gels: These may be either adhesives or form-in-place gaskets (gap fillers) and may be one component (1K) or two component (2K). These are thermoset materials that crosslink into a network that does not deform until the internal stress in the material resists further deformation.

Phase Change: While phase change TIMs are usually available as solids, they can also be applied as a liquid using hotmelt type processing. They behave like grease in thermal performance but are better in reliability due to less pump out.

The decision to pick a particular liquid TIM depends not only desired thermal performance but also manufacturing requirements such as: (1) component stress during assembly, (2) ability or need to post cure, (3) ability to rework, (4) storage or shelf life and (5) dispensing equipment costs. One can summarize the relative merits in the table below, with green signifying best (lower thermal impedance, lower stress, easy storage, lower cost etc.) and red denoting challenges.



	1k Gel Pre-Cured	1k Gel Curable	2k Gap Filler	Phase Change	Thermal Grease	Comments
Thermal Performance	🟨	🟩	🟩	🟩	🟩	Contact Resistance
Reliability	🟨	🟩	🟩	🟨	🟥	Pump out related
Rework	🟩	🟥	🟥	🟨	🟩	Adhesion to surfaces
Assembly Stress	🟥	🟩	🟩	🟨	🟩	Rheology
Storage	🟩	🟨	🟩	🟩	🟩	Reactivity Liquids
Dispensing Equipment	🟩	🟩	🟨	🟨	🟩	Complexity

Fig. 8 – Relative characteristics of liquid TIMs

ASSEMBLY AND PROCESSING

LEVELING/THIXOTROPY: For thick bondlines and longer open time between dispensing and assembly, a material with high yield stress that will flow easily when stressed – i.e. a thixotropic material – is suitable. For complicated geometry where liquid must flow and wet out varying topology there will be a need for a self-leveling material – i.e. one with no yield stress.

ASSEMBLY STRESS: Typically, a “bead” of material is applied using a thin nozzle, after which the material is compressed during assembly. The bead traces a pattern on one surface that allows all active areas to be covered once the assembly is made. Depending on the rheology, pattern and assembly speed, there will be stress on the assembly that must be accounted for.

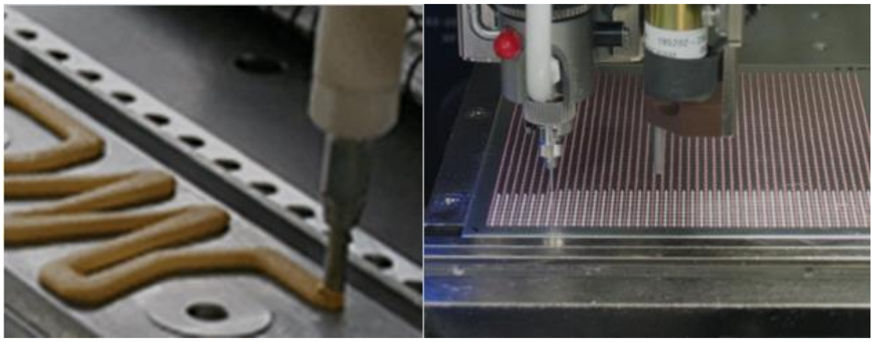


Fig. 9 – Liquid dispensed bead/dots patterned for full coverage

FILLER SEPARATION/CAKING: At high shear the particles may start aggregating; usually very high line pressure will cause this. In addition, if there are sharp corners or fittings, the particles may separate and accumulate in dead spaces. Finally, if the fitting is not designed well for the pressure needed for pumping, the polymer fluid could leak and cause the local concentration of filler to build up until a cake forms. All of these factors may contribute to clogging of tubing and fittings [18] – typically loose fittings or sharp corners are the most implicated in poor pumping performance. Equipment manufacturers are now taking these factors into account to produce more robust pumping systems.

ABRASION: Typical thermally conductive liquids contain abrasive ceramic particles. The process of pumping these materials initiates abrasion of moving parts that encounter the liquid. As such, the manufacturing must account for wear and replacement of worn parts or invest up-front in abrasion-resistant parts. Many equipment manufacturers of pumping and dispensing equipment have addressed these abrasion-related issues with innovative designs.

SHELF LIFE: As with other polymeric gasketing systems, liquid TIMs also have shelf life associated with loss of reactivity. In addition, one must account of settling of fillers during storage – this can typically be mitigated by remixing before application.

CONCLUSIONS

While the specification of TIM performance is driven by electronic design, one must also optimize manufacturing. Liquid TIMs offer not only better thermal performance, due to lower modulus during assembly and better wet out, but also allow increased manufacturing efficiencies. Better inventory management, automation optimization and quality control are possible with liquid TIMs, which are available in several formats to address both performance and manufacturing attributes. For the successful startup of a line, attention must be paid to storage, handling and dispensing these materials due to the particulate filler. These issues should be collectively addressed by TIM manufacturers, equipment manufacturers and the end user. There are several technically and economically viable solutions for automated dispensing of liquid TIMs on the market.

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