Nolato

**#2** Thermal management

# How different Thermal Interface Materials enhance the heat transfer between two components

White paper

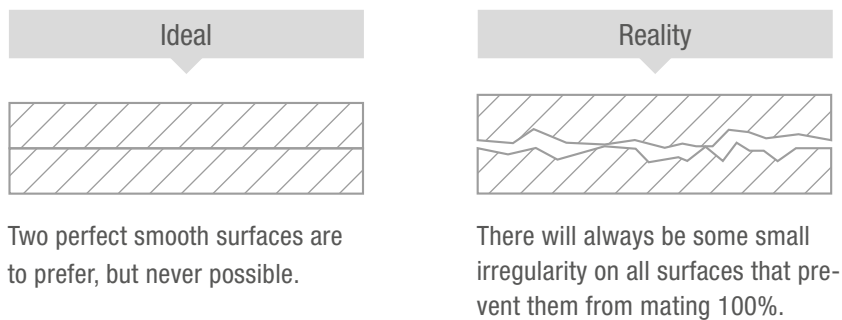# How different Thermal Interface Materials enhance the heat transfer between two components

All heat dissipation from a body occurs through its surface which forms an interface to the next medium or body. The surfaces are never perfect, and 96-98% of apparent contact area is air. This air gap is a big problem for heat transfer. Thermal Interface Materials (TIM's) displace the air in the interface to enhance the thermal connection between bodies. In order to reach the best possible result, it is important to understand how different TIM types affect your product.

All heat dissipation from a body, whether it is directly into the ambient, into an intermediate cooling medium, or into another body, occurs through its surface. This surface thus forms an interface to the next medium or body.

In electronics cooling, heat is commonly transferred from the source (e.g. an IC chip or package) to other bodies – heat spreaders, EMC covers, cold plates, heat sinks, and so on. This means that in a typical heat transfer chain, there will be at least one, but quite likely several such body-to-body interfaces for the heat to pass through before it reaches the ambient.

The problem with interfaces between solid bodies is that their surfaces are never perfect. They will not be completely smooth, as there is always some small irregularity or texture; they will not be completely flat, or completely planar – there will always be some tolerances on all surfaces that prevent them from mating 100%.

In fact, placing any two normal, industrially manufactured, ostensibly flat surfaces together will typically yield an actual solid-to-solid contact of only 2-4% of the nominal overlap. The other 96-98% of apparent contact area is empty space – i.e., air.

| Ideal | Reality |
|-------|---------|

Two perfect smooth surfaces are to prefer, but never possible.

There will always be some small irregularity on all surfaces that prevent them from mating 100%.

This is further compounded by the fact that the surfaces on either end of the interface aren't static. With varying power loads, ambient conditions, etc, they will see a variety of temperatures during operation. And with mismatches in CTE (Coefficient of Thermal Expansion) and other physical differences, changes in temperature over time will to some extent cause them to buckle and warp to varying degrees, further affecting how well – or how badly – the surfaces mate.

This introduces a potential variance in the interface gap over time, and a further increased difficulty in predicting the air gap in the interface.

This air gap is a big problem for heat transfer. With a thermal conductivity of a measly 0.02 W/(m·K), air is pretty much the best naturally occurring thermal insulator on the planet. Its presence will increase the thermal resistance over the interface significantly, causing the temperature at the heat source to rise.

Air

The air gap that occurs between two surfaces.

The air gap will cause the temperature at the heat source to rise.
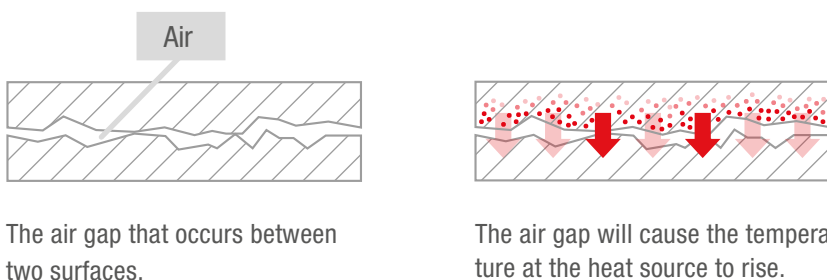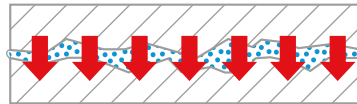
The solution to this problem is the Thermal Interface Material, or TIM.

The idea of using a TIM is to displace the air in the interface, and replace it with a material with two or three orders of magnitude higher thermal conductivity.

Regardless of type, this is the fundamental principle of all TIM's on the market.

TIM
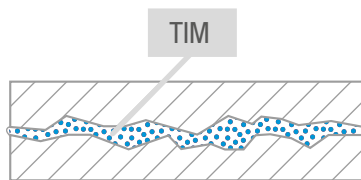
TIM displaces the air in the interface.

The material has higher thermal conductivity and enhances the thermal coupling between two surfaces.

## The importance to understand thermal Resistance

To understand why this is important, it is beneficial to revisit the concept of thermal resistance.

Thermal resistance is defined as follows:

$$R_\theta = \frac{\Delta t}{Q}$$

Where $\Delta t$ is the temperature difference in the system being studied [K or °C], $Q$ is the thermal power [W], and $R_\theta$ is the thermal resistance [K/W].

The corollary of this definition is:

$$\Delta t = Q \cdot R_\theta$$

Which tells us that given a constant thermal power, a reduction in resistance will create a reduced temperature difference. Since the ultimate cold-side temperature in most systems is given by the ambient temperature, a reduced temperature difference simply means a cooler heat source – a cooler component.

Analogously to Ohm's Law for electrical resistance, thermal resistances can be added as follows:

$$R_{\theta tot} = R_{\theta 1} + R_{\theta 2} + R_{\theta 3} + \cdots + R_{\theta n}$$

A typical, if somewhat simplified, resistance chain for an electronics application, describing the thermal path from junction to ambient, might then look like this:

$$R_{\theta(j-a)} = R_{\theta(j-c)} + R_{\theta(TIM)} + R_{(HS)}$$

Where $R_{\theta(j-a)}$ is the total resistance, $R_{\theta(j-c)}$ is component package's internal junction-to-case resistance, $R_{\theta(TIM)}$ is the resistance from the surface of the component package, through the TIM, to the surface of the heat sink's base, and $R_{\theta(HS)}$ is the resistance from the base of the heat sink, through the fins, and into the ambient air.

We can now readily tell that the thermal resistance at the interface will immediately affect the resistance of the whole, and thereby the temperature at the junction in our example.

The TIM's thermal resistance can be further subdivided into component resistances like this:

$$R_{\theta(TIM)} = R_{\theta(c-t)} + R_{\theta(m)} + R_{(t-h)}$$

Where $R_{\theta(TIM)}$ again is the total resistance, $R_{\theta(c-t)}$ is the contact resistance between the component package's and TIM's surfaces, $R_{\theta(m)}$ is the resistance through the material itself, and $R_{\theta(t-h)}$ is the contact resistance between the TIM's and the heat sink's surfaces.

The contact resistances depend largely on how well the TIM wets out the surfaces it mates against; how well it displaces air, and fills out minute irregularities and crevices. This in turn depends on the surface properties of the TIM, the pressure applied against it, cleanness of mating surfaces, roughness, and so on, and so forth. The contact resistances can therefore be difficult to predict accu-

rately. A general rule of thumb is that the softer and/or tackier a surface is, and the higher the pressure applied to it, the lower the resistance.

If we for simplicity assume isothermal surfaces, the resistance through the bulk of the TIM itself can however be defined by this familiar formula:

$$R_\theta = \frac{\Delta x}{k \cdot A}$$

Where $\Delta$x is the average bondline thickness [m], $k$ is the TIM's thermal conductivity [W/(m·K)], and $A$ is the contact area [m²].

It is the $k$ value in this formula that we improve by two or three orders of magnitude – i.e. by a factor of a hundred or a thousand – when we replace the air in a thermal interface with a TIM.

The effect of this on the total resistance is of course profound.

## Different types of TIM Application Architecture

There are two different basic application architectures in TIM application. We call these the "thin bondline" and the "thick bondline", or "gap filling", applications. "Bondline" is a term used for the distance between the two surfaces – the heat source and the heat sink – in the interface. Each of these have their own design approaches and proper TIM's to apply.

A "thin bondline" occurs when the surfaces are pressed directly against one another, and the distance – the bondline thickness – is defined only by the mean tolerances of the surfaces themselves, and/or by the deflectability of the material placed between them. Such applications are typically screw or spring mounted, and the bondline thickness would range somewhere around 10-200µm.

Examples may be:
> when an individual heat sink is mounted on top of an IC chip
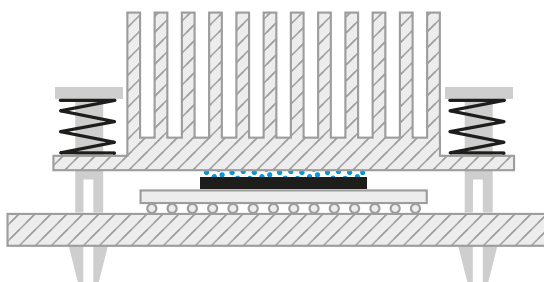
> when a large but relatively flexible heat source such as a LED MCPCB is screwed into heat sink.
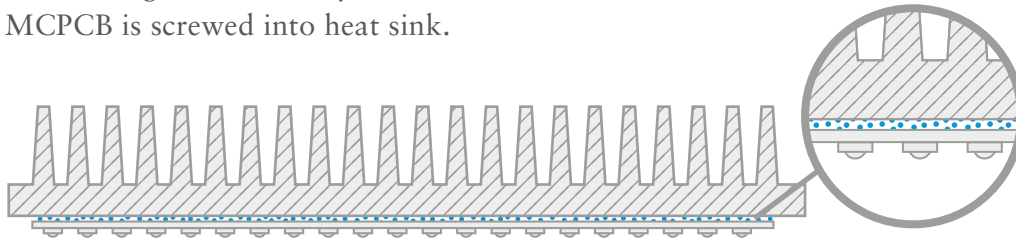
"Gap filling" applications on the other hand occur when there are larger tolerances at play – when the bondline thickness is defined by mechanical features in the application outside of the components themselves, or the tolerances are otherwise very rough. In this type of application, the forces keeping the surfaces in place will usually not go through the material itself, but through a mechanical hard stop. The typical range of "thick" bondlines is around 0.2-5mm.

Examples may be:

> When the surfaces, and therefore the range of flatness tolerances, are large.
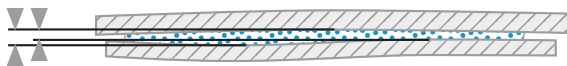
> When there is a multitude of different components of varying heights that need to be connected to a common heat sink through a common TIM.
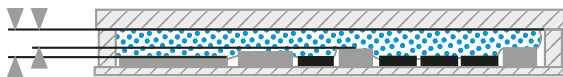
> When there is an assembly with a heat source on a PCB mounted inside a box, over which a lid with a heat sink is mounted, so that the final distance will be affected by the whole chain of tolerances from the component, through the board, the box, and finally the lid.
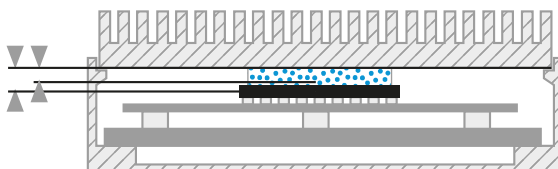
The choice between the thin and thick bondline architectures will be determined by two factors: mainly the thermal requirement, as with all things being equal, a thin bondline yields a vastly superior thermal performance. And second, by the mechanical requirements of the assembly in question.
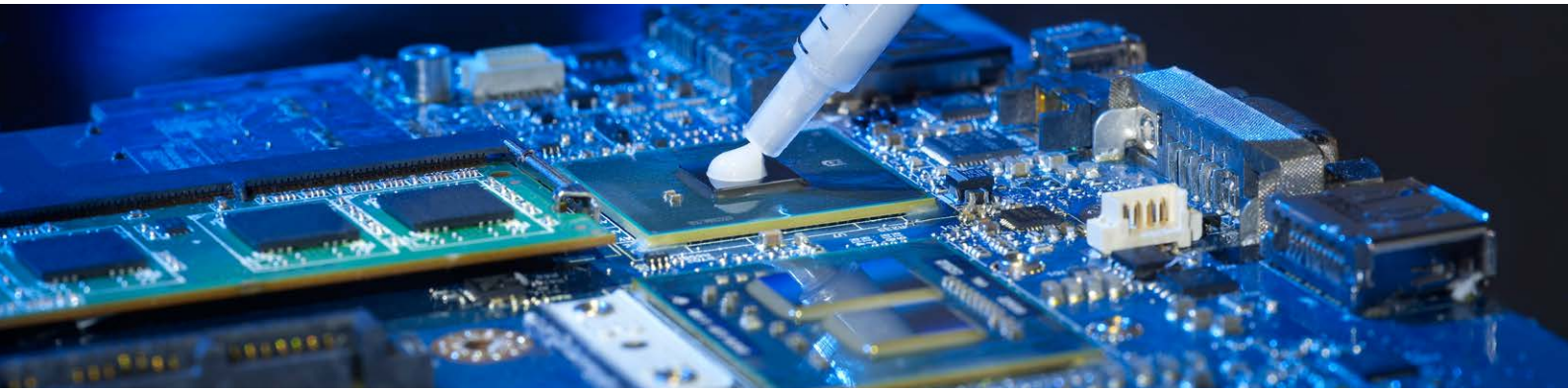
If the thermal and the mechanical requirements are at odds, a compromise must be sought, or the parameters for the mechanical requirement redefined because, if the thermal requirement is not met, the application will not function as intended.

Further parameters that affect the choice of TIM are:
> voltage differences – is there a voltage difference between the heat source and the heat sink, or along the surface of the TIM, that the TIM will need to insulate against?
> production parameters – will it be more rational to use solid or liquid materials, other considerations?
> compliance – are components or boards very sensitive to pressure?
> application environment – is the application's intended end use going to subject the TIM to environmental factors that render some TIM choices more or less suitable?

## Material Types and Application
Looking closer at the basic range of material types available for each of the architectures, we find a variety of materials developed for different preferences, mainly in terms of production. For both thin and thick bondline applications, there are both solid materials and liquid dispensed materials available.
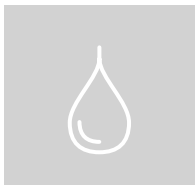
### Thin Bondline
Generally true for most thin bondline interface materials is that they achieve their performance mainly by two mechanisms:

**1.** By wetting out the surfaces in the interface very well, thereby efficiently displacing the air in the interface, thereby creating very low contact resistances between surfaces and TIM.
**2.** By allowing the interface surfaces to get very close to one another, thereby reducing the distance that heat is conducted through the TIM, thereby reducing the bulk resistance.

While the TIM has two or three orders of magnitude better conductivity than the air it replaces, it will still have one or two orders of magnitude lower conductivity than the metals it is commonly placed adjacent to. Therefore, in applications requiring the very highest thermal performances, being able to keep the TIM very thin is the key to the lowest resistance.

Putting this in relation to the formulae presented above, thin bond line TIM's operate by keeping the contact resistance components of the total TIM resistance small, and reducing the bulk resistance mainly by making the $\Delta x$ as small as possible.

The basic thin bondline TIM is the *thermal paste*; the evolutionary successor to the old thermal greases.

This is a liquid material that can typically be screen printed, usually by stencil but in some cases also by silk screen, or dispensed from a nozzle. Other application methods that may be employed are rolling, brushing, or raking, but these methods tend to yield less precision in the amount of material applied. Being wet, if they are not assembled directly after application, they need a protective cover or blister lest they attract dust and debris during transportation or storage.

Due to its intrinsically wet and viscous nature, this material type can achieve very thin bondlines under pressure, and wet out the contact surfaces very well. All this adds up to a very low thermal resistance; even more so for the high performance variants.

Where the old greases tended to be highly prone to dry-out (when the binding agents evaporate, just leaving a dry powder) and pump-out (see below), as well as eager to bleed oil, most modern pastes have few or none of these drawbacks.
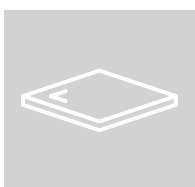
The second thin bondline TIM is the *phase-change material, or PCM*.

This material typically comes as a dry, pre-cut pad that is placed on either the component or the heat sink, and then placed under pressure between the two when the surfaces are assembled together. The material can be left in place for an indefinite time after application awaiting assembly, usually being protected by a film tab or liner.

During initial burn-in, when the heat source reaches its operating temperature for the first time, the TIM pad will be heated above its phase-change temperature (typically in the range 40-60°C), and soften to a more viscous state – basically, change from a solid to a liquid phase; hence, "Phase-Change Material".

Europe
+46 582 88900

North America
+1 651 955 9505

China
+86 135 0188 1054

Malaysia
+60 4505 7830

India
+91 98847 22707

Korea
+82 106621 6580

Email: silikonteknik@nolato.se
www.nolato.com/thermal

This more viscous state material will then in principle act as a grease, and achieve a similar type of thin bondline and good wet-out, and hence good thermal performance.
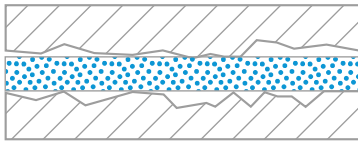


PMC is placed in the interface.
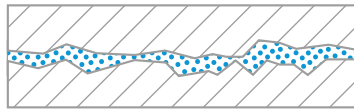
When the material is heated during initial burn-in, it softens to a viscous consistency.

When the application is powered down and cools below the material's phase change temperature, the TIM will naturally solidify, but it will by then have moulded itself to the final shape. Repeated heating/cooling cycles will usually not alter the thermal performance.

Special variants of PCM's include materials that are applied as rub-on stickers, materials that come on either side of an electrical insulator foil, materials that are applied to a thin metal foil to allow re-work, materials that are screen printable, etc. All of these offer special properties and advantages for particular applications.

## Two things important to keep in mind

There are two things that are important to keep in mind when using the thin types of bondline TIM's above.

**1** First is the fact that these materials will relax after assembly – this is true for pastes as well as PCM's, but this behaviour is particularly pronounced for PCM's during the burn-in cycle: paste will flow and adjust itself to surfaces under pressure, and PCM will melt and do likewise. As these materials are mounted with direct pressure between heat source and heat sink, there is a risk that with a static screw mount, the torque may loosen.

Therefore, a measured amount of overtorque, spring/clip mounts, or re-torque after a certain interval (after burn-in, in the case of PCM's) is always recommended.

**2** Second is that depending on the application, there may be a greater or lesser danger of pump-out.
Pump-out is what occurs when surfaces flex due to CTE mismatches, and the TIM between them is not thixotropic enough to withstand the pumping action this flexing generates, but is forced out of the interface.

It is of course important to choose good quality materials with low pump-out to start with, but with PCM's it is also important to consider the peak operating temperatures of the components in the application. By definition, phase-change materials will have a temperature dependant viscosity. Some PCM's thus become very runny indeed when temperatures exceed 120-130°C, at which point they may become susceptible to pump-out.
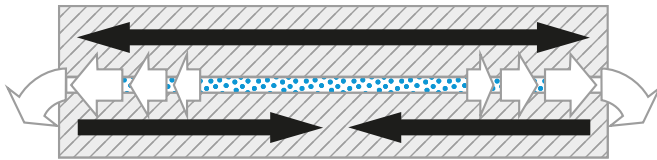


Therefore, it is recommended to test materials during your design process and ascertain their suitability to the specific application you are designing.

## Graphite film – a third type of "thin" bondline
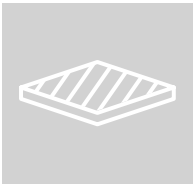
A third type of thin bondline material, not affected by the above, is the *graphite film*.

This material type operates on a diametrically opposite principle to other thin bondline TIM's.

It accepts a higher contact resistance and slightly thicker bondline, instead reducing the TIM's bulk resistance by using a high conductivity material.

These materials are generally placed simply as a piece of foil in the interface. Through-plane thermal conductivities are perforce quite high; values in the range of 15W/(m·K) and more are not uncommon.

While they have the advantages of never suffering from either pump-out, dry-out, or bleeding, and also being simple to handle in production as well as completely without mess in re-work, graphite pads also have the disadvantage of being quite hard. Also, being completely dry, they have no wet-out whatsoever. This means that they require very high mounting pressures to force the graphite pad to conform to surfaces at all.
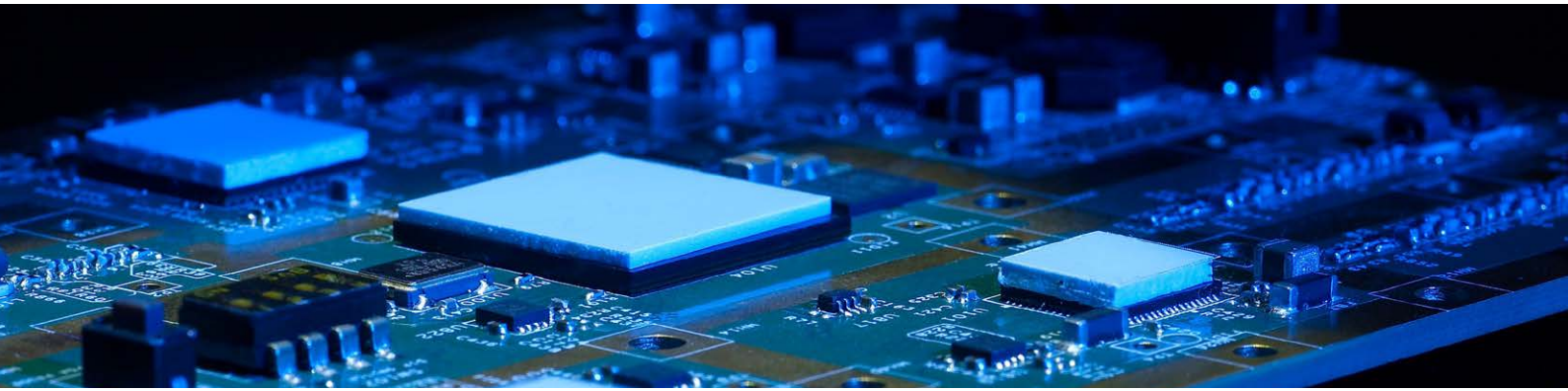
## Gap Filling materials

Generally true for the gap filling thick bondline materials is that they need to conduct the heat over a longer distance while still offering a reasonable thermal resistance, and that they need to be able to withstand a significant degree of deflection in order to be able to mitigate the tolerances that come with gaps in mechanical designs.

This material category also achieves its task through two main mechanisms:

1. By being soft and compliant, they can deflect, flow, and conform to surfaces very well, thereby reducing contact resistance also against surfaces with macro variations; liquid filler materials and the inherent tackiness of certain pad materials enhance this property by good wet-out
2. Bulk resistance is addressed through the brute force approach of striving for ever higher thermal conductivities.

This material category accepts the necessity of a thick bondline to handle issues in the mechanical design that for one reason or another preclude mating cooling surfaces directly against the heat sources, or that otherwise create large tolerance spans between the two.

In terms of the formulae in the earlier section, the approach of these materials is to strive to keep the contact resistance components of the total TIM resistance as small practically possible, and compensate for the bulk resistance imposed by the large $\Delta$x by making the $k$ large enough to still provide an adequate thermal solution.

It is however inescapable that as this material category is required to solve multiple tasks at once (e.g. conduct heat and bridge gaps, mitigate macro tolerances) it will perforce also constitute more of a compromise. This is good within its specific scope, but unlikely to be the best answer for the most demanding thermal problems. For those, a thin bondline material will always be the go-to solution.
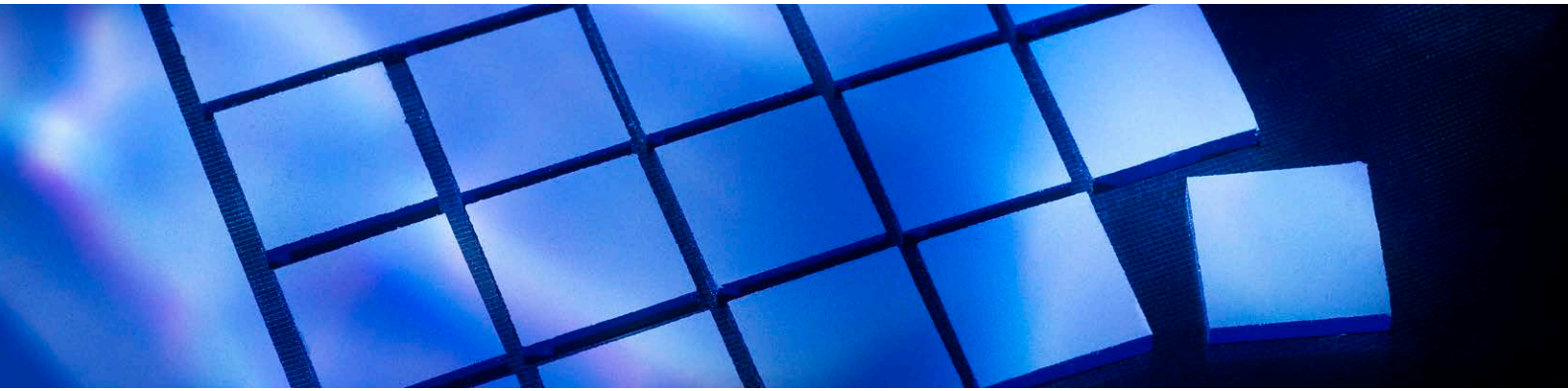
## The first type – soft pad.

Pads come in a vast variety of material types, with different conductivities, pressure/deflection responses, hardnesses, tackinesses, electrical insulations and so forth. Each available in a range of thicknesses and other options.

These materials are typically delivered pre-cut to a certain geometry, ready to mount in place on a component or a heat sink. Depending on the manufacturer, it may also be possible to further customise materials with different surface characteristics, reinforcement materials, and other special properties. This material type can be mounted in place an indefinite time prior to assembly, with a liner or tab to protect tacky variants.

There is thus a large number of parameters that may enter into the picture when designing for these materials. One key parameter to bear in mind however that these pads are elastomers. Their viscoelastic nature makes them behave in a viscous manner under certain circumstances, and an elastic manner in others.

One consequence of this is that there is a maximum as to how much they can be deflected. They will flow under pressure to a point, but ask them to flow too much, and they may start breaking apart. But being viscoelastic, under constant pressure they will never stop deflecting, meaning that designing in a mechanical hard stop that does not go through the material is strongly recommended.

Overly aggressive deflection is generally to be avoided, as even before the material is in danger of breaking, it may start to exude its polymer matrix, being in most cases silicone. Therefore, following the maximum deflection recommendations – most often 50% of nominal thickness; there are also materials that can withstand as much as 70% deflection without adverse effects – is highly advised.

Also, the materials depend on a slight deflection – no less than 10% – to achieve a good thermal contact.

## Why the tolerance span in the gap is important

Therefore, when selecting the proper thickness of the material, the tolerance span in the gap needs to be considered. Considering the example of a material that has a maximum recommended deflection of 50%, the entire tolerance span of the gap needs to fit into that 10-50% deflection span of the material. Thus, if you know the tolerance, you know the material thickness, and thereby also the nominal gap you need to draw in.

Another consequence of the viscoelastic nature of these materials is that the force with which they resist deflection is dependent on the rate of deflection. The faster you try to deflect them the more elastic their response; the slower, the more viscous.

Therefore, in applications where the forces exerted in the thermal interface are a key concern, allowing more time to tighten the assembly together is a good way to reduce the force.

## The second type – dispensed filler

This type divides into two subcategories: the two-part cure-in-place filler, and the one-part non-curing filler.

One of the foremost advantages of either filler-type material is that as they are entirely viscous during assembly, they can be deflected to their minimum thickness – usually just a few tenths of a millimetre – irrespective of the original thickness. This makes it possible to optimise the design for much thinner bondlines than with pads, even when tolerance spans are large.



From a production standpoint, these materials are primarily suitable for automated dispensing, meaning potentially low production costs, particularly in high volumes. Again, due to their viscous state during dispensing and assembly, the material will exert very little stress on components in the assembly phase, even with rapid rates of deflection.

Further, from a logistic standpoint, as the materials usually are machine dispensed, the fact that the material's geometry is deter-

Europe
+46 582 88900

North America
+1 651 955 9505

China
+86 135 0188 1054

Malaysia
+60 4505 7830

India
+91 98847 22707

Korea
+82 106621 6580

Email: silikonteknik@nolato.se
www.nolato.com/thermal

mined only by the programming of the dispensing equipment, all instances it is dispensed in will be from the same BOM listing. This obviates the need for separate items and part numbers for separate TIM geometries.

However, the drawback is that the material used in all TIM instances on a board need to be determined by the worst case. The possibility for optimisation of individual instances is limited.

*Two-part (2p) fillers* come, as the name suggests, in two parts that are mixed together during the dispensing process. The material then cures within a certain time (usually several hours) after dispensing, during which time frame final assembly must be made.

As the material being dispensed in a liquid state but subsequently cures in place, the material can be allowed to be quite fluid in its liquid state, meaning that flow rates in dispensing can be reasonably high. It also mean that that wet-out can be very good, and contact resistances thus can be low even at low contact pressures.

As these materials freeze upon curing to precisely fit the geometry they form to during assembly, 2p fillers are resilient to vibration and CTE movement in the final application. These are therefore highly recommended e.g. for the automotive industry.
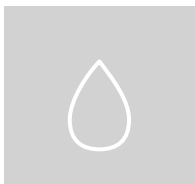
*One-part (1p) fillers,* also known as gels, do not cure after dispensing, but remain in a viscous state indefinitely.

This means that assuming that protection from dust and debris is provided for, final assembly can be arbitrarily separated in time and distance from the dispensing.

The fact that these materials will be required to stay in place on their own after assembly even if the bondline gap is quite wide, does also mean that these materials need to have a higher viscosity from the start than their 2p counterparts. This can in some instances mean lower flow rate and slower production, and also that they may not flow into the very smallest nooks and crannies as willingly; nor wet out quite as readily, in turn meaning that the thermal performance may not be quite up to the level of the alternatives.

When applying 1p fillers, as these will remain in a liquid state indefinitely, applications with aggressive vibration and/or CTE mismatch conditions are recommended to take precautions in the hardware design to ensure the material is unable to escape the bondline, or else consider using a 2p filler.

### A third bondline type – the compromise

A special case of interface material that falls somewhere between the thin and thick bondline architectures is the rubber film.

This material type usually consists of a carrier membrane of some kind coated with a thermally conductive rubber compound. The thickness is usually a few 1/10th's of a millimetre, and like soft pads, they are generally delivered pre-cut to a given geometry.

They are applied under direct pressure between heat sink and heat source just like the thin bondline materials, but are thicker, and do not wet surfaces at all as effectively. They do flow under pressure to some slight degree, but are relatively speaking hard.

These materials are primarily used in applications where very good electrical insulation is required between heat source and heat sink, and/or the interface pressure is high.

The same basic composition is also commonly used as a base for double-sided thermal adhesive tapes.

## Conclusion

All heat dissipation from a body occurs through its surface. This surface thus forms an interface to the next medium or body. The problem with interfaces between solid bodies is that their surfaces are never perfect. And this is affecting how well – or how badly – the surfaces mate. In fact, 96-98% of apparent contact area is air, and this air gap is a big problem for heat transfer. The idea of using a TIM is to displace the air in the interface, and replace it with a material with two or three orders of magnitude higher thermal conductivity. There are different types of TIM application architecture, and in order to reach best possible result, it is important to understand how they affect your product.



Replace the air gap with TIM
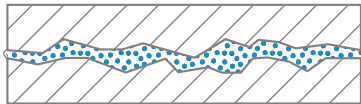
The right TIM improves the product's thermal connection.

## If you want to know (even) more

We are able to offer you the support that you seek to obtain optimal performance and cost savings in electronics cooling. We offer you our own thermal management solutions (TIMs) and possess extensive experience of thermal solutions design across a broad range of industry applications. Are you interested in knowing more about how the latest technologies can be applied to your products to the best affect? Welcome to contact us.

### Contact
Name: Jussi Myllyluoma
Phone: +46 73 3341302
Mail: jussi.myllyluoma@nolato.com