Thermal Capabilities of Solder Masks and Other Coating Materials – How High Can We Go?

Sven Kramer
Lackwerke Peters GmbH & Co. KG
Kempen, Germany

Abstract

This paper focuses on three different coating material groups which were formulated to operate under high thermal stress and are applied at printed circuit board manufacturing level. While used for principally different applications, these coatings have in common that they can be key to a successful thermal management concept especially in e-mobility and lighting applications. The coatings consist of:

Specialty (green transparent) liquid photoimageable solder masks (LPiSM) compatible with long-term thermal storage/stress in excess of 150°C. Combined with the appropriate high-temperature base material, and along with a suitable copper pre-treatment, these solder resists are capable of fulfilling higher thermal demands. In this context, long-term storage tests as well as temperature cycling tests were conducted. Moreover, the effect of various Cu pre-treatment methods on the adhesion of the solder masks was examined following 150, 175 and 200°C ageing processes. For this purpose, test panels were conditioned for 2000 hours at the respective temperatures and were submitted to a cross-cut test every 500 h. Within this test set-up, it was found that a multi-level chemical pre-treatment gives significantly better adhesion results, in particular at 175°C and 200°C, compared with a pre-treatment by brush or pumice brush. Also, breakdown voltage as well as tracking resistance were investigated.

For an application in LED technology, the light reflectivity and white colour stability of the printed circuit board are of major importance, especially when high-power LEDs are used which can generate larger amounts of heat. For this reason, a very high coverage power and an intense white colour with high reflectivity values are essential for white solder masks. These "ultra-white" and largely non-yellowing LPiSM need to be able to withstand specific thermal loads, especially in combination with high-power LED lighting applications.

The topic of thermal performance of coatings for electronics will also be discussed in view of printed heatsink paste (HSP) and thermal interface paste (TIP) coatings which are used for a growing number of applications. They are processed at the printed circuit board manufacturing level for thermal-coupling and heat-spreading purposes in various thermal management-sensitive fields, especially in the automotive and LED lighting industries. Besides giving an overview of the principle functionality, it will be discussed what makes these ceramic-filled epoxy- or silicone-based materials special compared to using "thermal greases" and "thermal pads" for heat dissipation purposes.

Introduction

The demands and loads placed on photoimageable solder masks rise to unknown new levels. Today’s solder masks are already exposed to a considerable level of thermal stress, high humidity and/or condensation. Especially in automotive electronics, the level specified for thermal resistance and thermal cycling resistance is constantly increasing. Due to higher currents and applications mounted in the engine compartment/gear box or close to the exhaust system, common photoimageable solder masks reach their performance limits. The thermal stress resulting from higher operating temperatures triggered the development of new solder masks or further development of existing solder masks. Here, the level demanded by the industry in terms of permanent high temperature loads is typically 175°C.

Photoimageable solder masks

While an LPiSM can consist of more than twenty different ingredients – which are of course all needed to create a coating which can be easy, fast and reproducibly processed in the specified quality – the actual "backbone" of such a coating is made up of only three components: The resins, fillers and hardener. These constituents ultimately determine the (di)electrical and physical/mechanical properties. Table 1 and Table 2 give an overview of a principle LPiSM formulation composition.

Table 1 – Constituents resin component LPiSM

Raw material	Property
Resins/binders	Photoreactive and thermally cross-linking resins, decisive for adhesion, insulation/ resistance
Fillers	Adhesion, scratch resistance, hardness, flow behaviour (thixotropy), thermo-mechanical properties
Dyes/pigments	Colouring substances
Additives	Adjusting wetting, flow, defoaming, etc.
Solvents	Viscosity adjustment, control of drying

Table 2 – Constituents hardener component LPiSM

Raw material	Property
Photoinitiators	Initiate photopolymerisation in exposure, influence on exposure time/energy and resolution
Solvents	Viscosity adjustment, control of drying
Hardener	Cross-linking medium of the thermally curing resins, decisive for resistance and physical and chemical final properties of the coating

Ageing process of polymers

When looking at the most relevant factors involved in the general ageing of polymers the following considerations come to mind. First, a loss in volatile components, e.g. a loss of low-molecular weight components that were present from the beginning. Furthermore, oxidations that are often accompanied by an increase in cross-linking and embrittlement. The continuation of molecular polymerisation often initially leads to an increase in electrical and mechanical stability, but finally ends in embrittlement. Additionally, the chemical separation of low-molecular weight components plays a role. This separation is a result of the ageing process. These processes can act autocatalytically. Finally, also a hydrolysis of the polymer due to present moisture needs to be considered.

General procedure for long-term temperature storage testing of LPiSM

The approach for LPiSM testing consisted of the application (20 to 40 µm dry thickness) and processing of different coating materials on various (high Tg, low CTE) substrates followed by a surface finish (ENIG = electroless nickel immersion gold, IMT = immersion tin or HASL= hot air solder levelling). Prior to the actual testing a pre-conditioning consisting of one wave soldering or two reflow soldering processes was carried out before the actual temperature storage conditioning. The intermediate or subsequent testing procedures listed below were conducted with a screen printing LPiSM having a 20 µm dry thickness.

- Breakdown voltage testing
- Tracking resistance (CTI)
- Adhesion using different pre-cleaning modes

The thermal performance of high temperature-resistant LPiSM cannot be viewed as an isolated entity. It must always be looked at in combination with the substrate used and its treatment (i.e. cleaning, degreasing, deoxidation). Without a matching (Tg/CTE) laminate, even the best possible pre-treatment prior to solder mask coating will not lead to the desired results in terms of adhesion and inevitably lead to fissures and cracks as shown in Figure 1.

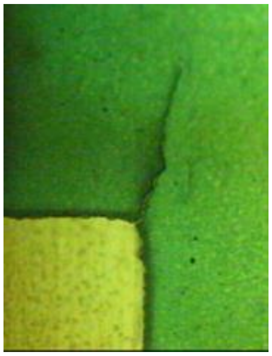


Figure 1 – Corner crack of an LPiSM on laminate/Colour change – Relevant or not?

Figure 2 shows the colour change of an LPiSM before and after a thermal load of 2000 h at 175°C and 200°C, which is acceptable to most as long as the insulation properties are within tolerances. The discolouration is caused by a certain degradation/oxidation of the pigmentation and binders. Depending on the actual coating tested, electrical properties can, of course, decline (e.g. insulation resistance) and must be looked at individually.

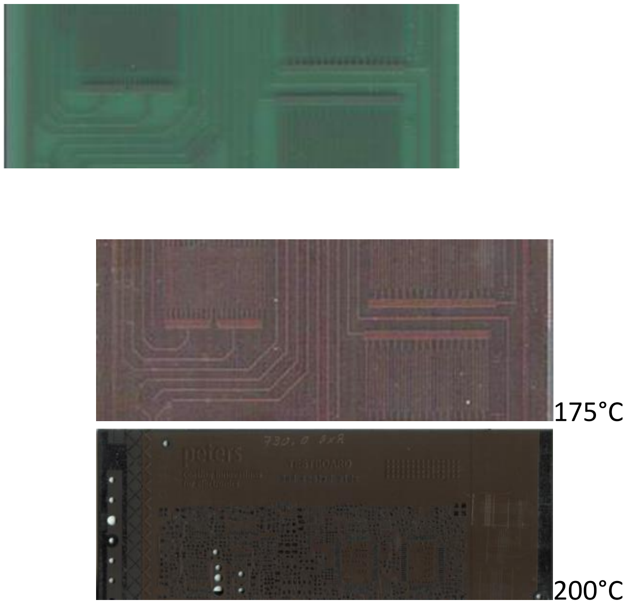


Figure 2 – Visual appearance of LPiSM before and after 2000 h storage at 175°C and 200°C/
Influence of pre-treatment on solder mask adhesion

Figures 3 to 5 very clearly show the impact of pumice brushing, brushing and a (multi-level) chemical pre-treatment at 150°C, 175°C and 200°C for up to 2000 h conditioning time in combination with an aqueous-alkaline developable LPiSM specifically formulated for high temperature storage applications with a matching laminate. The results of the cross-hatch test according to EN ISO 2409 show that a purely mechanical treatment will not enable a long-term thermal storage/resistance even at 150°C.

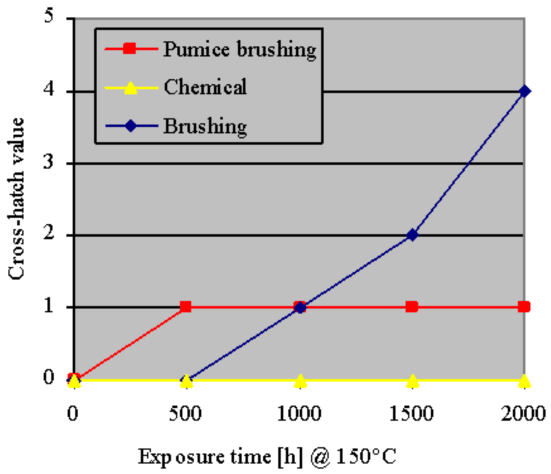


Figure 3 – Adhesion of LPiSM after temperature storage at 150°C

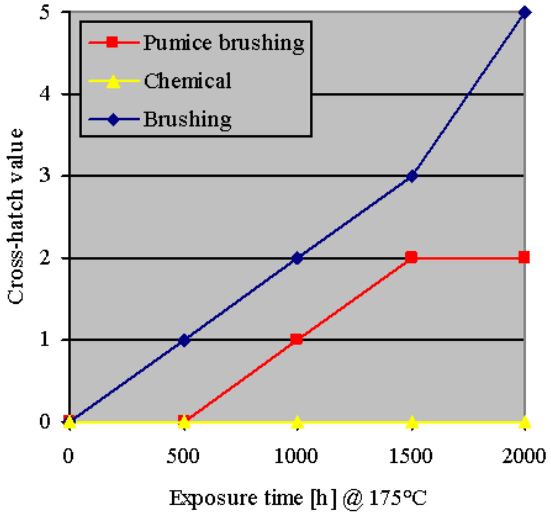


Figure 4 – Adhesion of LPiSM after temperature storage at 175°C

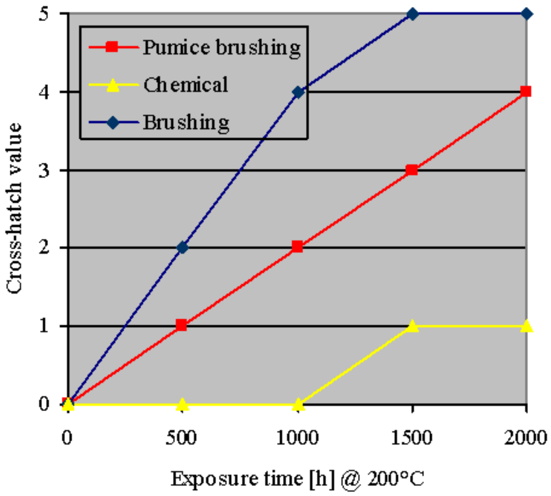


Figure 5 – Adhesion of LPiSM after temperature storage at 200°C

The measuring of breakdown voltage on a steel plate with 20 µm dry thickness, Figure 6, during 200°C storage for a total of 20 days indicates that with increasing thermal load insulation generally decreases and begins to fluctuate after approx. 10 days. This can potentially be caused by fissures and pores or microbubbles.

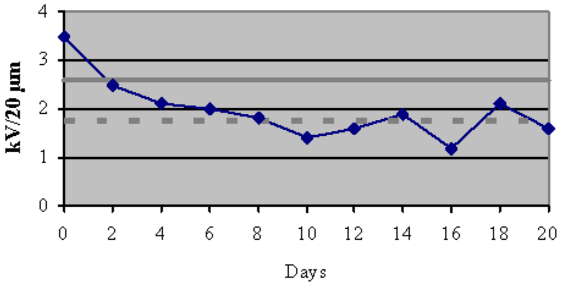


Figure 6 – Breakdown voltage during temperature storage at 200°C (coated steel plates)

Figure 7 shows that the aim at least to maintain the CTI value of the laminate can be met even after a 2000 h thermal load at 175°C with specialty coatings.

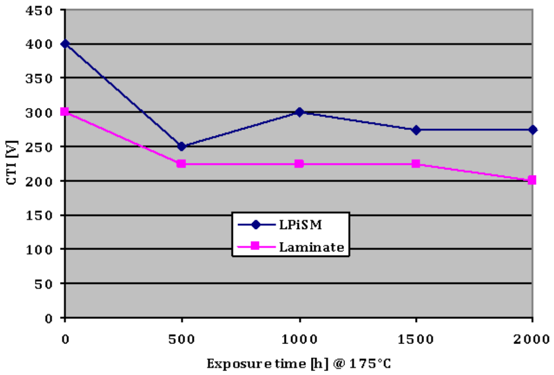


Figure 7 – Tracking resistance after temperature storage at 175°C

The Tg and CTE values as indicated in Table 3 seem to be largely independent on the curing temperature. An additional triple reflow soldering process at 265°C appears to lead to a post cross-linking because the corresponding Tg values increase by approx. 20°C.

Table 3 – Dependency of Tg on curing temperature (+ 3x reflow)

Conditioning of specimen	Tg [°C]	CTE < Tg [ppm]	CTE > Tg [ppm]
60 min @ 150°C	152	45	90
60 min @ 160°C	145	48	99
60 min @ 170°C	153	44	97
60 min @ 180°C	140	53	104
60 min @ 150°C + reflow	169	50	80
60 min @ 160°C + reflow	173	52	90
60 min @ 170°C + reflow	178	42	85
60 min @ 180°C + reflow	171	39	84

The severe thermal load applied as indicated in Table 4 leads to a slight increase in the Tg and a (more favourable) lower CTE. The mechanism is presently not understood. However, it can be summarised that the tested LPiSM shows a high stability of Tg and CTE over a wide temperature range, which obviously can be advantageous when thermal shock/temperature cycling, and long-term thermal storage are carried out.

Table 4 – Dependency of Tg on curing temperature + 3x reflow + thermal ageing

Conditioning of specimen	Tg [°C]	CTE < Tg [ppm]	CTE > Tg [ppm]
+ 500 h @ 150°C	177	29	39
+ 500 h @ 160°C	175	31	38
+ 500 h @ 170°C	177	28	35
+ 500 h @ 180°C	180	22	29
+ 1000 h @ 150°C	173	24	34
+ 1000 h @ 160°C	173	15	21
+ 1000 h @ 170°C	176	18	26
+ 1000 h @ 180°C	182	17	22

Defining ultra-white and largely non-yellowing LPiSM

Even though the following group of coatings discussed principally also belongs to the "LPiSM family," these are very different in certain aspects from the previously discussed ones. The most important and obvious difference is the fact that the color impression is not created by using dye-stuff which leads to a transparent coating film but is achieved by using an insoluble white pigment (usually TiO_2) which is supposed to largely hide the substrate.

In order to describe a color or a difference in color from a quantitative point of view, one can illuminate the surface to be measured by means of a defined light source and measure the light that has been remitted. In mathematical calculations both the type of the light source and the color impression of the eye is considered for measuring "color". To characterize a color through values the so-called CIE Lab System (to be precise, the L*, a*, b* system of the CIE – Commission international de l'éclairage, International Commission on Lumination) as shown in Figure 8, is commonly referenced. This lab system is based on the transformation of the primarily calculated color values X, Y, Z to the coordinates L* (brightness), a* and b* (yellow-blue-value).

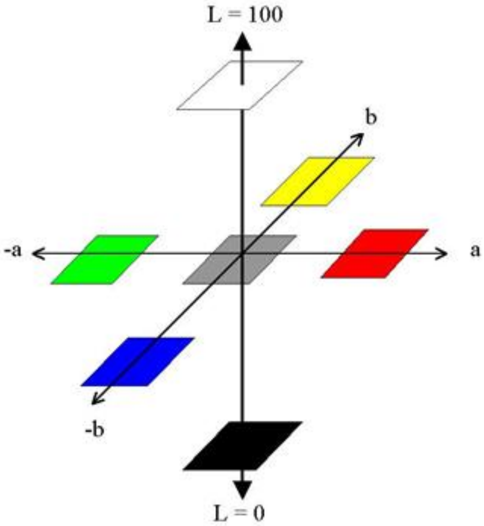


Figure 8 – Scheme of the CIE L*a*b* system and its color coordinates

The major benefit of the CIE lab system is its suitability for determining color distances. The value defining a color distance, i.e. the similarity or identity of colors, is ΔE*, which is calculated as a special Pythagoras from the three values $L_1^* – L_2^*$, $a_1^* – a_2^*$ and $b_1^* – b_2^*$:

$$\Delta E^* = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

In view of describing a white surface one can either use a reflectivity graph (see Figure 9 which shows various reflectivity levels depending on LPiSM type and thermal stress applied) or the brightness value L* from the CIE lab system. According to the definition, a perfectly white surface would have the coordinates L* = 100, a* = 0 and b* = 0. As an advantage, the CIE lab system restricts the values to be measured to no more than three figures and provides the option of forming differences that largely correlate with the color perceived.

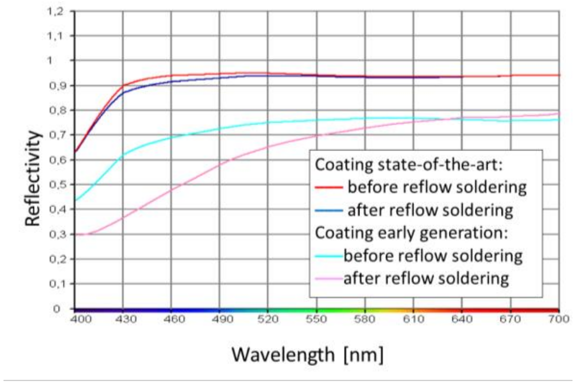


Figure 9 – Reflectivity graphs of a white "classical" and new-generation LPiSM

This approach is very helpful also in the case of white LPiSM for the electronics/printed circuit board field. Besides an evaluation in accordance with the CIE lab system, there is also the possibility of defining color changes – i.e. yellowing – as it is practiced, for example, by the paper industry according to DIN 6167. Based on DIN 6167:1980-01, one speaks about yellowing if a non-desired yellowing value is recognized with the material observed, in consequence of its handling. From the primarily calculated X, Y and Z values, a yellow value G is obtained. The change of the yellowing degree between an untreated (G_0) and a treated specimen (G_1) is calculated and referred to as the yellowing value V.

The color coordinates of the CIE lab system, i.e. the values L*, a* and b*, can be directly measured by means of colorimetric devices. Differences as visible to the eye are indicated as follows:

Δb* = 0–1: not visible in general
Δb* = 1–2: low yellowing, only visible by the trained eye
Δb* = 2–3.5: medium difference, visible by the untrained eye
Δb* = 3.5–5: distinct difference
Δb* > 5: strong difference

This assessment can also be transferred, in good approximation, to the interpretation of the pre-cited ΔE*, ΔL* and Δa* values. Given the widespread acceptance of the AE*, ΔL* and Δa* values for describing color distances and/or color changes, it is recommended to apply these data.

White LPiSM – Covering power

A basic feature of colored coating materials is the so-called covering power which indicates the performance in covering the color, or color difference, of the base material. As a criterion, a contrast ratio is predefined between the contrasting areas of the base. The covering power is achieved by absorption and diffusion and is a function of the color-giving pigments. In the case of white pigments, it is only a consequence of diffusion. The covering power depends on both the layer thickness and the respective contrast with the base and has a characteristic limit. The covering power cannot be adapted to any thickness of layer. The minimum layer thickness required for a white covering coating in a black-white contrast is approx. 40 µm. Unlike thermal curing solder resists, UV curing coating materials – including LPiSM – must be slightly transparent in order to ensure a sufficient UV cross-linking down to the substrate.

There are certain consequences for processing, given the physical limits of the covering power. This way, a 10 µm thick layer looks less white than a layer of 20 µm, and again a 30 µm layer seems to be whiter than a 20 µm layer. Typically for a layer thickness of approx. 40 µm or higher, the white color no longer depends on the layer thickness since maximum covering power has been reached. Within color evaluations and measurings of a layer thickness below maximum covering power, i.e. lower than approx. 40 µm, the base material has to be included in the evaluation. This means that the reflectivity graph and the L* value also depend on the layer thickness,Figure 10.

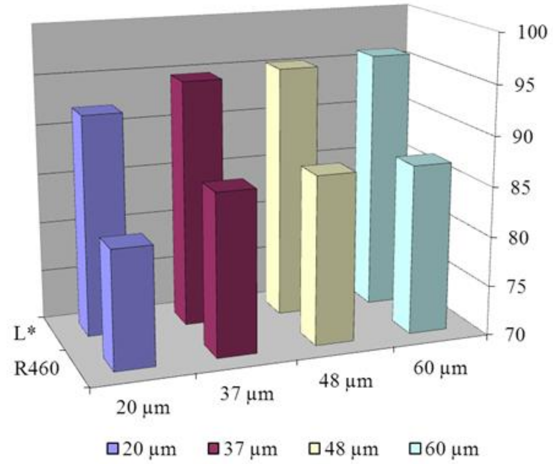


Figure 10 – Reflectivity or L* value of a white solder mask depending on the layer thickness

When processed, solder resists undergo several thermal loads which may have a visible impact on the (white) color. This is particularly valid for the soldering process which causes a shift towards the yellow color, i.e. yellowing. A white solder resist supplied to the assembler should undergo the least possible color change in subsequent solder processes.

As for the underlying mechanism, there are different causes for yellowing:

- Heat
- Sunlight
- Environmental influences (e.g. humidity, chemicals).

In this context, it is primarily yellowing by heat or sunlight, or by a sunlight-simulating time-lapsed UV radiation that takes place. Light-induced yellowing is produced whenever light beams fall on polymers with a wavelength of less than 380 nm (UV radiation). So-called chromophore groups producing a discoloration are created through radically-induced photochemical reactions. Heat-induced yellowing is the formation of such chromophore groups that are produced when polymers are exposed to temperatures > 100°C for a longer period of time.

The color change can be expressed by the so-called yellowing value on the one hand, or by measuring the color distance in the CIE lab system on the other.

In order to define this color change, the previously described color distance ΔE^* can be applied. The two values ΔL^* and Δb^* shall be given particular attention in case of purely white surfaces. While ΔL^* describes the change of brightness, Δb^* defines the blue-yellow shift, i.e. the yellowing effect in this case (see Figure 4). The Δ value, as low as possible, stands for the quality of the color stability of the solder resist, with differences of less than 0.5 being hardly perceivable for the untrained eye.

Besides the fact that very low levels of discoloration are desired and reflectivity is anticipated to be in the range of 95% for the most advanced white LPiSM, also thermo-mechanical properties are considered and the coating is expected to withstand thermal cycling without displaying fissures or cracks (e.g. IMT/HASL finish, 3x reflow conditioning, 500 cycles -40/+125°C). Figures 11 and 12 show an example of occurring/non-occurring fissures as a consequence of thermo-mechanical fatigue, which are of course unacceptable.

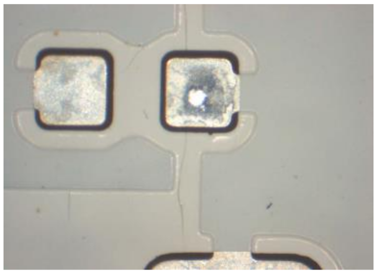


Figure 11 – Fissures and cracks after 500 cycles -40/+125°C

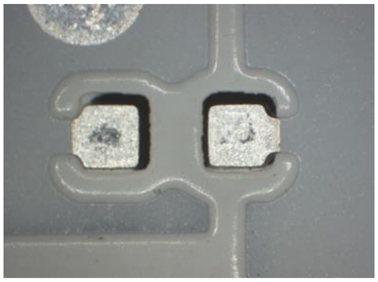


Figure 12 – Coating with no fissures/cracks after 500 cycles -40/+125°C

Introduction to screen-printed heatsink pastes (HSP) and thermal interface pastes/coatings (TIP)

The density of the electrical component assemblies on printed circuit boards is constantly growing because more complex circuits have to be located in smaller areas (miniaturisation). This development and the use of high-performance components that sometimes produce a high loss of power in the shape of heat necessitate a specific dissipation of the generated heat away from the source to the environment. The failure to apply this technology would result in an overheating of the components that would entail malfunctions and, in the worst case, even a destruction of the component. In some applications matters are made worse by the fact that elevated temperatures already exist at the PCB's place of operation.

To achieve a good heat dissipation, the use of metal heatsinks is very common. These heatsinks are mostly metallic cooling elements which are connected to the PCB and, on the one hand, ensure the heat dissipation from its source owing to the good heat conduction of metals and, on the other hand, enable the dissipation of the heat to the environment because of the large surface towards the ambient air. The capability of conducting heat – the thermal conductivity – is a specific characteristic. Metals have the best thermal conductivity, followed by inorganic solids. Next in line are organic solids and liquids. Gases have the poorest thermal conductivity. Table 5 contains some figures regarding this subject.

Table 5 – Thermal conductivity λ of various materials

	λ in W/m K
Tin, aluminium, copper	64, 200, 400
Air	approx. 0.02 - 0.03
Polymers	approx. 0.2 - 0.4
Interface/heatsink paste	approx. 2.0 - 3.0

Process steps in conventional heatsink assembly

The technology described for the assembly of bonded heatsinks has the disadvantage of constituting a very labour- and thus cost-intensive procedure. To begin with, the metal foils serving as heatsinks have to be punched into corresponding shapes which requires the manufacture and operation of respective punching tools. A double-sided bonding film must then be applied to the punched-out heatsink which afterwards must be positioned on the printed circuit board. Following the positioning process on the PCB, the metal foil has to be coated with corresponding coating systems for electrical insulation and protection from corrosion. For this process, defined coating thicknesses with the matching electrical and dielectric properties are required. As these heatsinks are usually several 100 µm high, an adequate edge coverage cannot always be realised with sufficient process safety. As a rule, a surface pre-treatment of the metal foil is required additionally in order to produce a good adhesion which, for instance, is required for a subsequent wave or reflow soldering process.

As a rule, the process steps listed cannot be automated and, therefore, have to be performed manually. Thus, these operations are highly time- and cost-consuming and the result obtained is not equal to the required precision of a mechanical production.

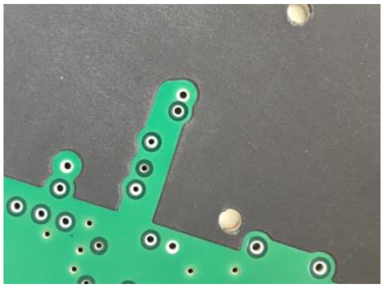
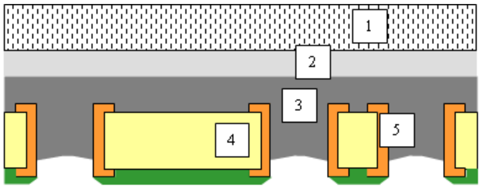


Figure 13 – Example of a screen-defined, printed and cured HSP on a PCB

For some applications, such as street LED lighting or other power applications in which PCBs are under operative high voltage, a double insulation layer can be necessary or even required by law. This situation can be solved by the combined application of the HSP as shown in Figure 13 and the screen-printable TIP over the heatsink. The hardness of the HSP will efficiently support the application of the TIP. For this purpose, the HSP is used for filling heat vias and for heat spreading. The optimum connection to the heatsink is ensured by the TIP (Figures 14 and 15).

Figure 14 – Example of a screen-defined, thermal interface paste printed on a PCB with underlying heatsink paste and its lighting application



1 = Cooling element
2 = Printed thermal interface paste
3 = Printed heatsink paste
4 = PCB core
5 = Heat via

Figure 15 – Combination of heatsink paste and thermal interface paste

Compared to alternatively used materials like greases, foils and adhesives, the TIP has a number of advantages. Reference is made here to the simplified – in particular automatable – processes.

Structure of the TIP/HSP

The pastes consist of special polymer matrixes so that the system can be applied to the printed circuit board by means of the screen or stencil printing process and will be functional after a thermal curing process. The polymers (EP-based in case of HSP and SR in the case of TIP) are filled with special, finely dispensed solid particles which ultimately ensure the required thermal conductivity. The ideal printable heatsink is available as a 1-pack system, is solvent-free and can be cured without any problems in usual curing units, convection dryers or IR drying units. To allow for assembly, the materials are resistant to wave/reflow soldering.

Comparison of thermally conductive grease and thermal pads with TIP

Thermally conductive grease improves the efficiency of a heatsink, but it is subject to a kind of "pump-out effect" related to temperature variations. Such an effect causes a moving of the grease away from the original requested position, reducing – in the long term – its efficiency. Furthermore, the application of such grease is not one of the most preferred process steps as it is not a very clean operation.

Thermal pads are a pre-formed square or rectangle of solid material which are cut to fit. They are made of solid material with the same function as thermal grease and can be electrically insulated or not, adhesive or not. As an alternative to thermal grease they are cleaner, no "pump-out effect" occurs and generally they are easier to install. However, thermal pads conduct heat less effectively than a minimal amount of thermal grease as their typical thicknesses are higher than 120 µm, but most commonly used are 200 µm or more.

Generally, the cost level is much higher compared to thermal grease. Besides, the pre-cuts are performed from dimensionally standardised rolls, so that the total cost of such thermal pads is strongly influenced by the dimensions and shapes of the parts to be interfaced.

Screen-printable solder-resistant Thermal Interface Paste (TIP)

A technically advanced solution is a screen-printable TIP, a paste which is electrically insulating and soldering resistant. Application and curing is done by the substrate manufacturer on the bare PCB selectively in the specified layout and prior to soldering. In this way, the end users will receive the PCBs with the TIP already "on board". The typical end thickness after screen printing and curing is between 50 and 70 µm. Since there is no pump-out effect, the thermomechanical decoupling properties are ensured even in permanent thermal cycles.

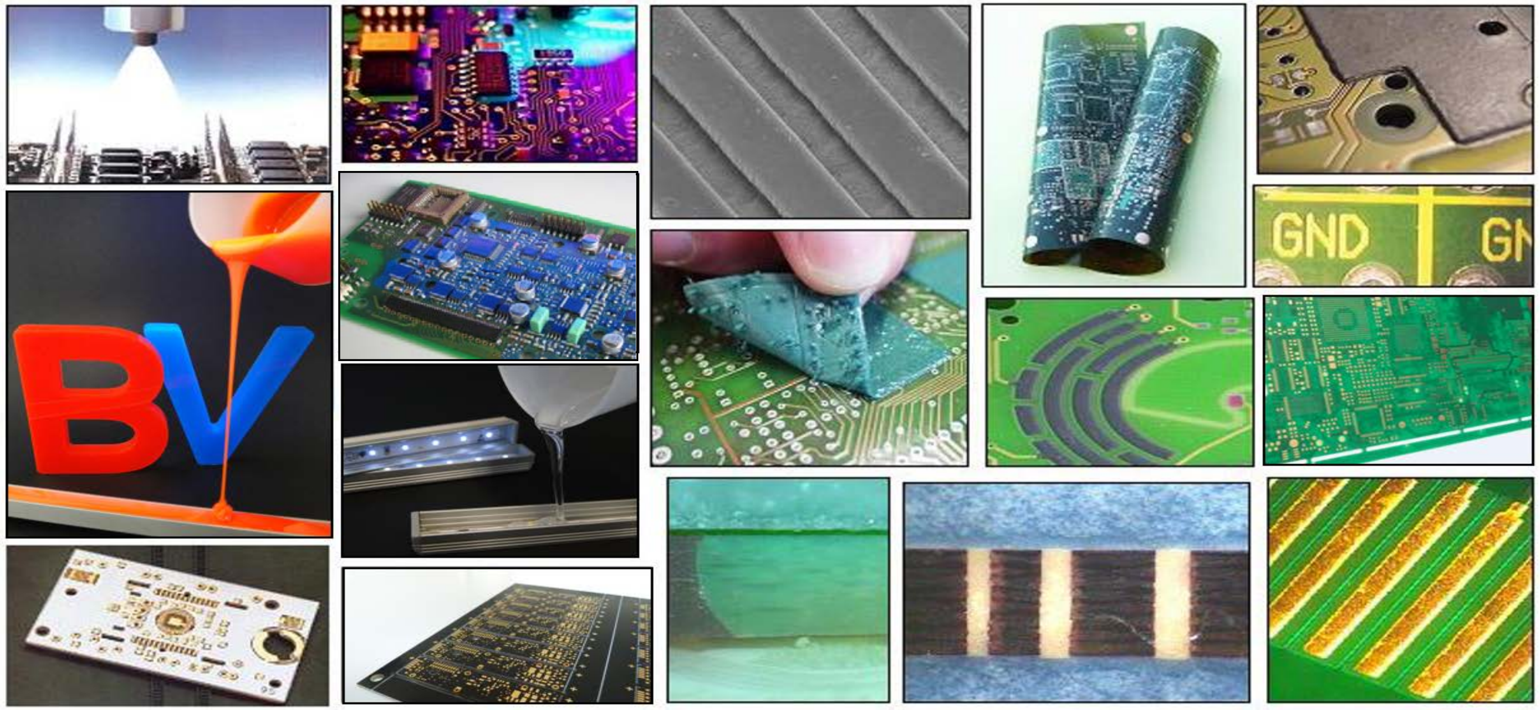
Summary

Presently, the long-term thermal resistance for specialised LPiSM is 175°C. Suitable LPiSM have a Tg of around 170°C. Adhesion and insulation performance are on a similar level compared to "standard" 150°C long-term resistance coatings. Only a suitable substrate treatment prior to LPiSM coating will allow to achieve the desired results. Of course, suitable high-Tg substrates must be used to avoid thermal mismatches and resulting cracks. 200°C long-term thermal resistance is presently not possible. While the adhesion level is good, insulation properties largely suffer after long-term exposure. The mechanism is not yet understood.

Thanks to the colorimetric approach as used in many coating fields, it is also possible in the printed circuit board/electronics industry to exactly define, compare and monitor the level of white and its stability under different conditions. When it comes to ultra-white and non-yellowing LPiSM, the latest available generation of ultra-white LPiSM typically shows a reflectivity in the range of 0.9 at dry thicknesses of only 20 µm, which means that due to the increased covering power considerable material savings compared to many existing materials can be made.

Heatsink pastes and thermal interface pastes used for heat dissipation purposes are on the rise. The fact that these screen-printable, 1-pack curable and electrically insulating coatings are processed by printed circuit manufacturers and can be brought easily and accurately into virtually any screen- or stencil-defined shape and thickness has further increased their acceptance as thermal interface materials (TIM) in many electronic fields where thermal management is of growing importance, as in e-mobility applications with high currents and lighting applications with high-power LED generating high levels of heat which needs to be dissipated.

Thermal Capabilities of Solder Masks and other Coating Materials – How High can we go?



Sven Kramer
Lackwerke Peters GmbH & Co. KG
Kempen, Germany

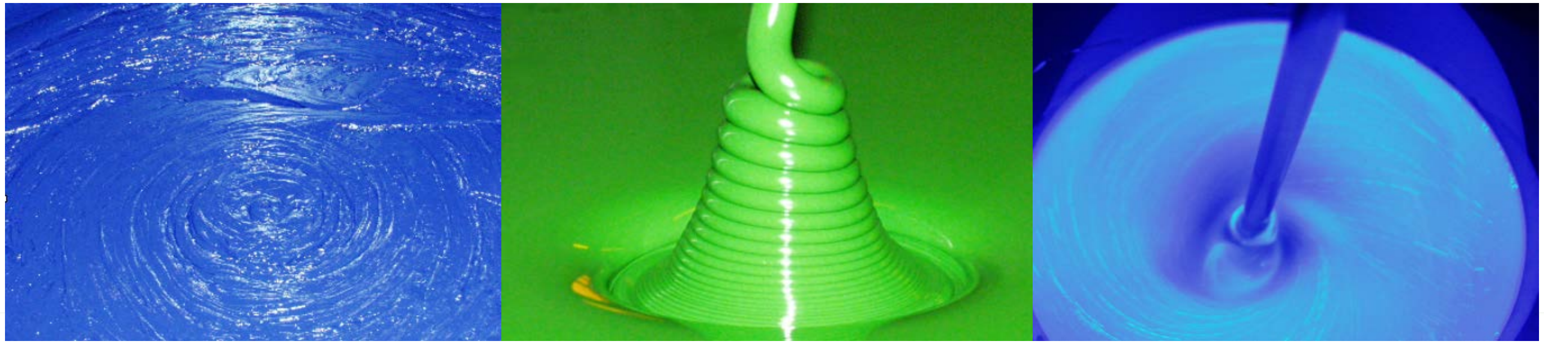
Principle Liquid Photoimageable Solder Mask Composition

“Resin component“ LPiSM

Raw material	**Property**
Resins / binders	Photoreactive and thermally cross-linking resins, decisive for adhesion, insulation / resistance
Fillers	Adhesion, scratch resistance, hardness, flow behaviour (thixotropy), thermo-mechanical properties
Dyes / pigments	Colouring substances
Additives	Adjusting wetting, flow, defoaming etc.
Solvents	Viscosity adjustment, control of drying

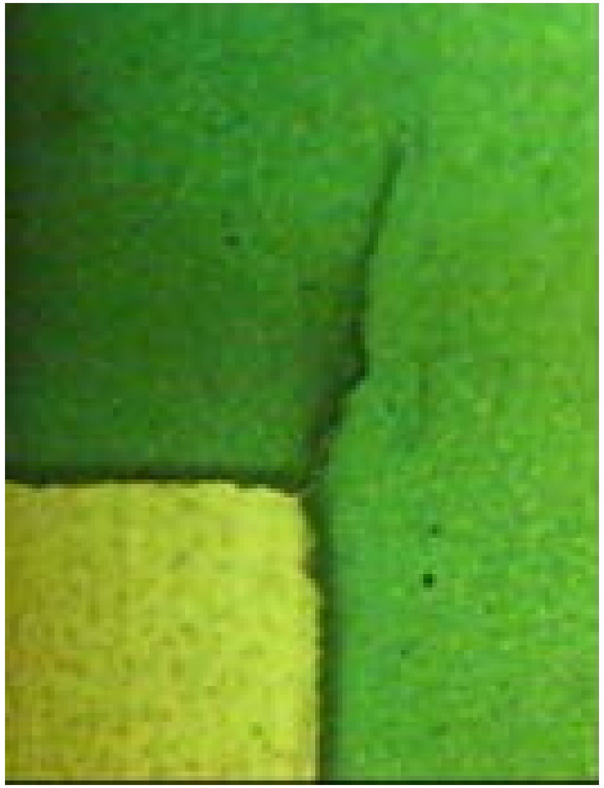
“Hardener component“ LPiSM

Raw material	**Property**
Photoinitiators	Initiate photopolymerisation in exposure, influence on exposure time / energy and resolution
Solvents	Viscosity adjustment, control of drying
Hardener	Cross-linking medium of the thermally curing resins, decisive for resistance , physical and chemical final properties of the coating



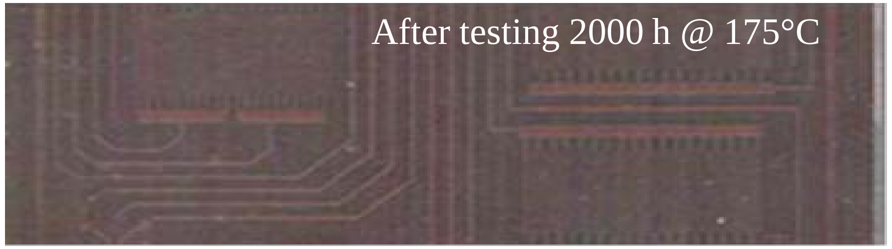
Applying thermal stress to LPiSM

“Corner Crack“ LPiSM



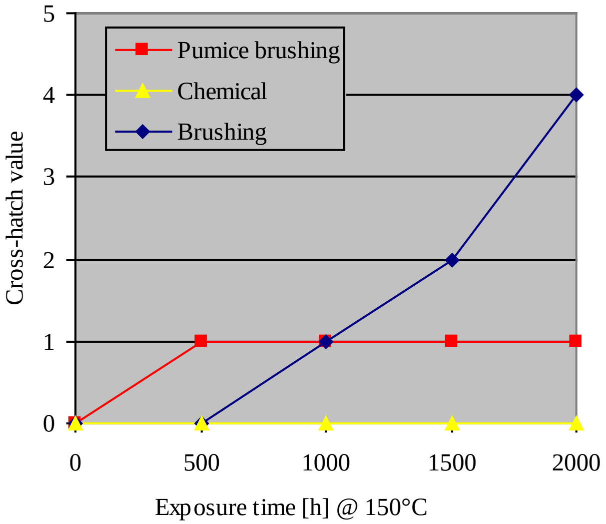
Colour change LPiSM depending on thermal load

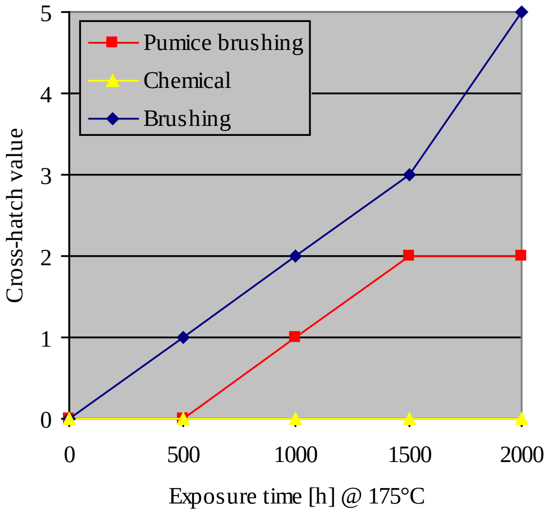

Before testing

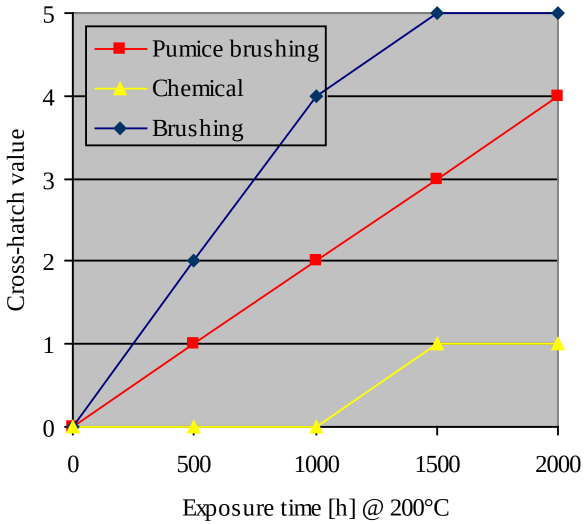

After testing 2000 h @ 175°C


After testing 2000 h @ 200°C

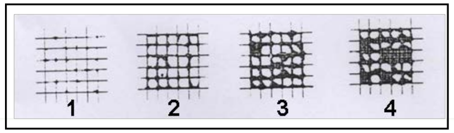
Influence of pre-treatment on LPiSM adhesion

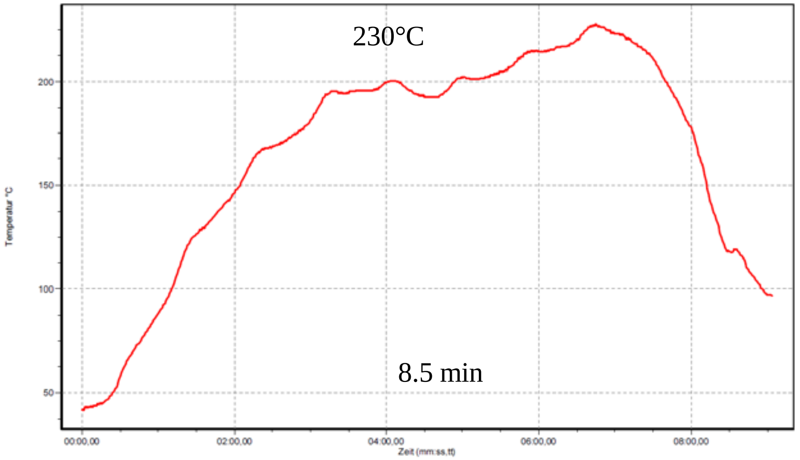




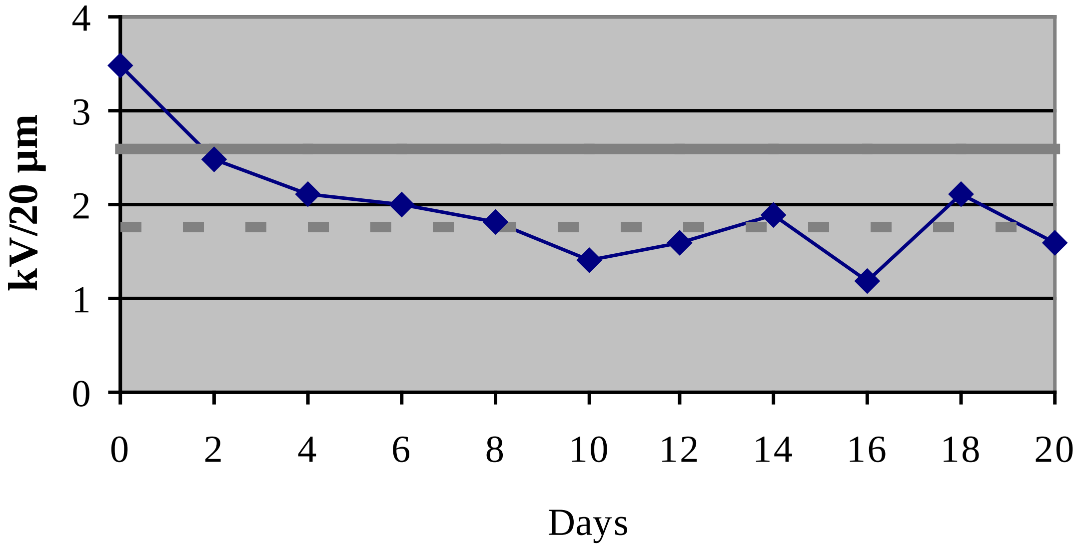


Cross-hatch value (Gt)	Percent loss of adhesion
0	0%
1	~ 5%
2	~ 15%
3	~ 35%
4	~ 65%
5	≥ 65%

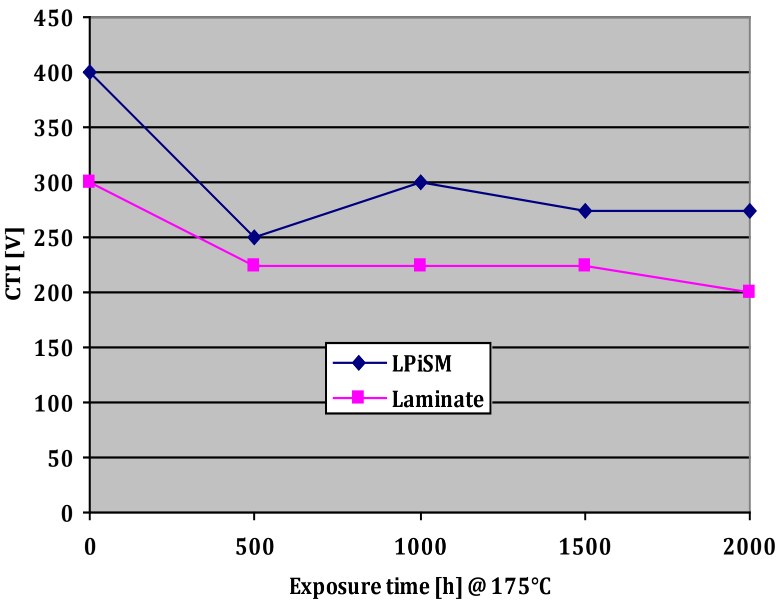




Influence of pre-treatment on LPiSM adhesion



Breakdown voltage during temperature storage at 200°C
(coated steel plates)



Tracking resistance after storage 175°C

Thermal stress to post crosslinking of LPiSM

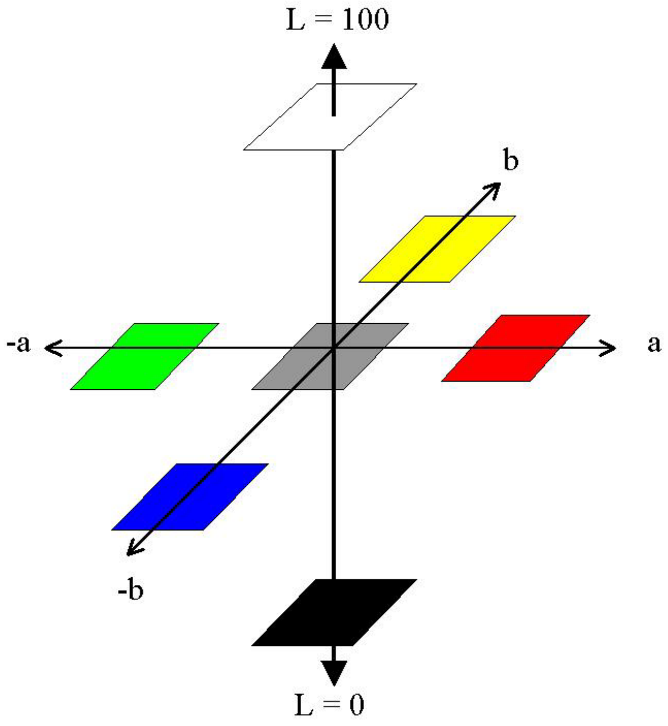
Conditioning of specimen	Tg [°C]	CTE < Tg [ppm]	CTE > Tg [ppm]
60 min @ 150°C	152	45	90
60 min @ 160°C	145	48	99
60 min @ 170°C	153	44	97
60 min @ 180°C	140	53	104
60 min @ 150°C + reflow	169	50	80
60 min @ 160°C + reflow	173	52	90
60 min @ 170°C + reflow	178	42	85
60 min @ 180°C + reflow	171	39	84

Dependence Tg on curing temperature(+ 3x reflow)

Conditioning of specimen	Tg [°C]	CTE < Tg [ppm]	CTE > Tg [ppm]
+ 500 h @ 150°C	177	29	39
+ 500 h @ 160°C	175	31	38
+ 500 h @ 170°C	177	28	35
+ 500 h @ 180°C	180	22	29
+ 1000 h @ 150°C	173	24	34
+ 1000 h @ 160°C	173	15	21
+ 1000 h @ 170°C	176	18	26
+ 1000 h @ 180°C	182	17	22

Dependence Tg on curing temperature(+ 3x reflow + ageing)

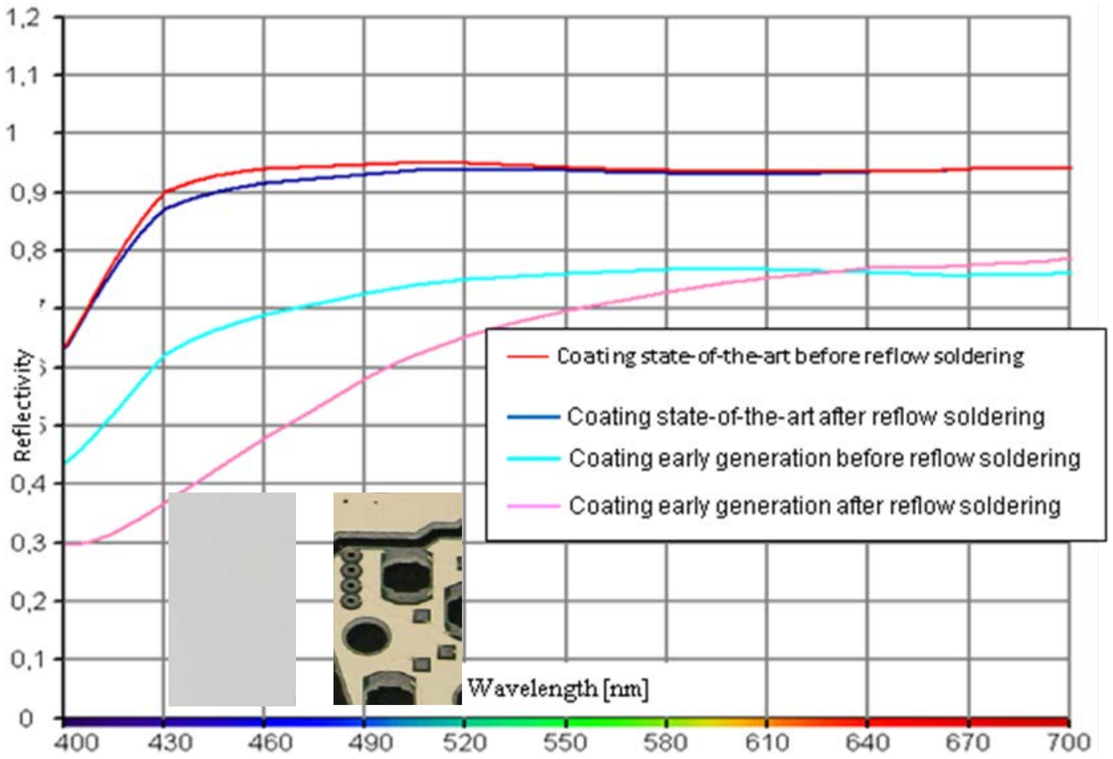
Defining colours – “ultra-white“ and non-yellowing LPiSM

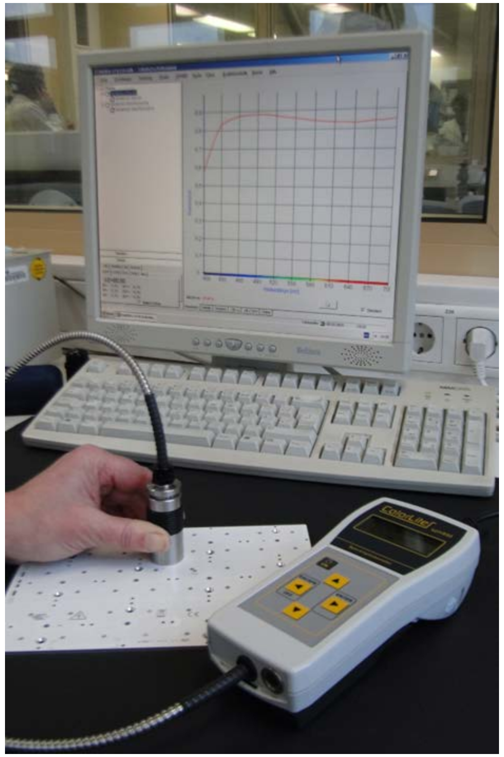


$$\Delta E^* = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

- $\Delta b^* = 0–1$: not visible in general
- $\Delta b^* = 1–2$: low yellowing, only visible by the trained eye
- $\Delta b^* = 2–3.5$: medium difference, visible by the untrained eye
- $\Delta b^* = 3.5–5$: distinct difference
- $\Delta b^* > 5$: strong difference

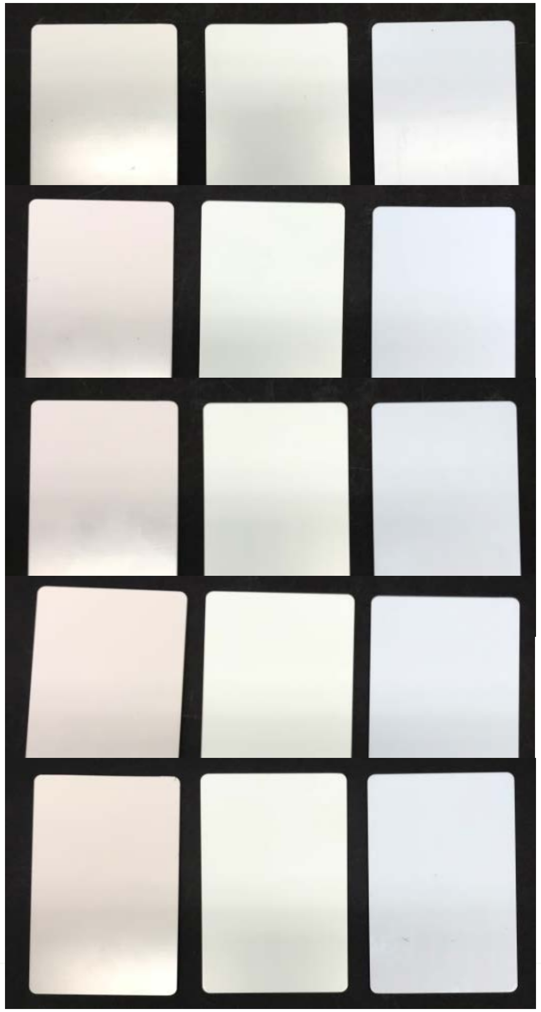
Defining colours – “ultra-white“ and non-yellowing LPiSM





Reflectivity graph of a white „classical“ and new generation LPiSM

Defining colours – “ultra-white“ and non-yellowing LPiSM



As cured

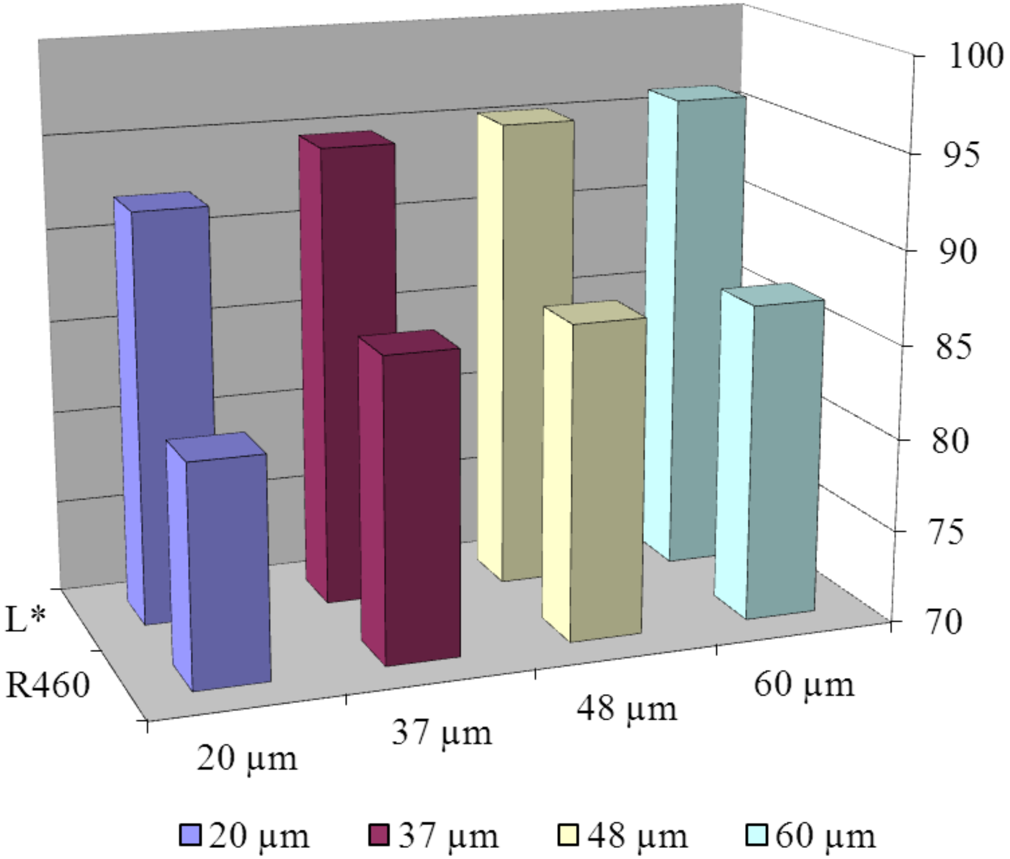
1 x reflow soldering

2 x reflow soldering

2 x reflow soldering
+ 1000 h @ 125 °C

2 x reflow soldering
+ 1000 h @ 140 °C

Defining colours – “ultra-white“ and non-yellowing LPiSM

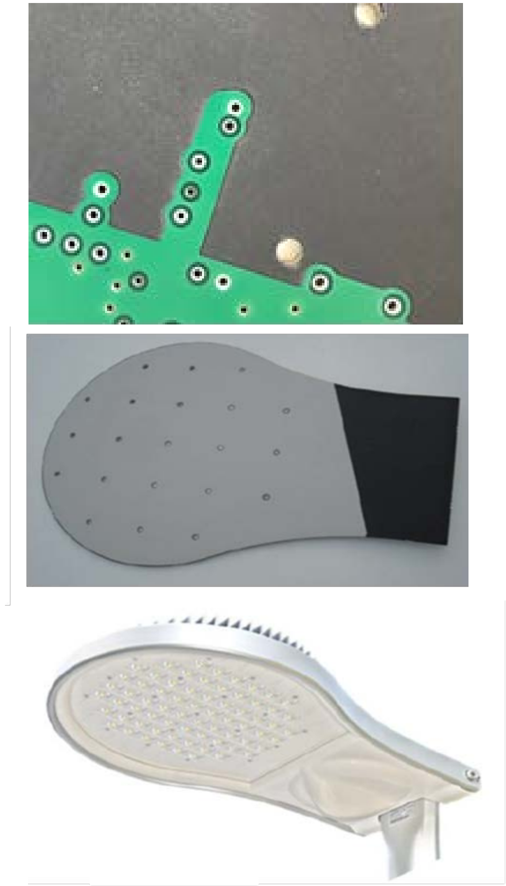


Reflectivity or L* value of a white solder mask depending on layer thickness

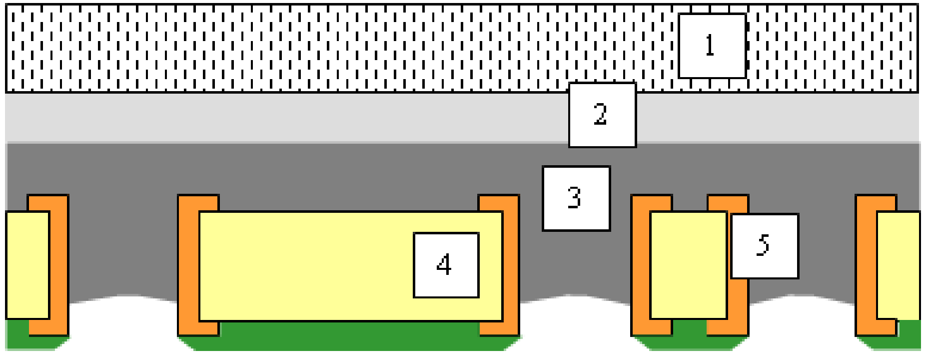
- Finish IMT / HAL
- Conditioning 3 x Reflow
- 500 cycles -40 / +125°C
- Assessment 10 – 30 x

“Thermo-mechanical fatigue”

Examples of coatings with heat dissipation characteristics

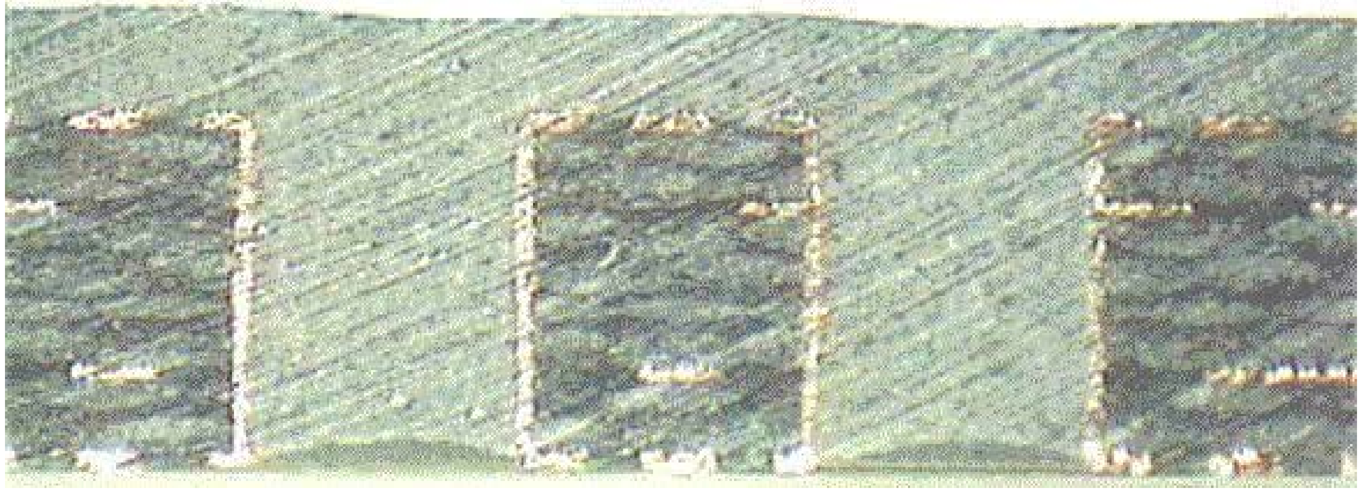


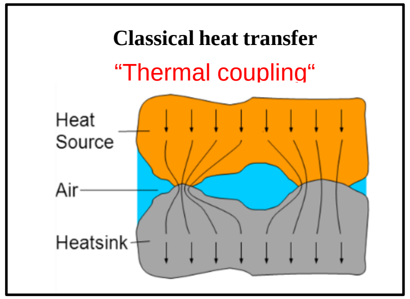
Material	λ in W/m K
Tin, aluminium, copper	64, 200, 400
Air	approx. 0.02 – 0.03
Polymers	Approx. 0.2 – 0.4
Interface-/heatsink-paste	Approx. 2.0 – 3.0



1 = Cooling element
2 = Printed thermal interface paste
3 = Printed heatsink paste
4 = Pcb core
5 = Heat-via

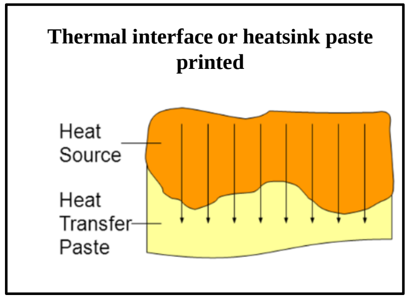
Examples of coatings with heat dissipation characteristics



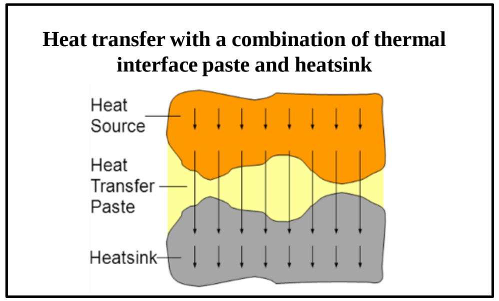


Classical heat transfer

“Thermal coupling“

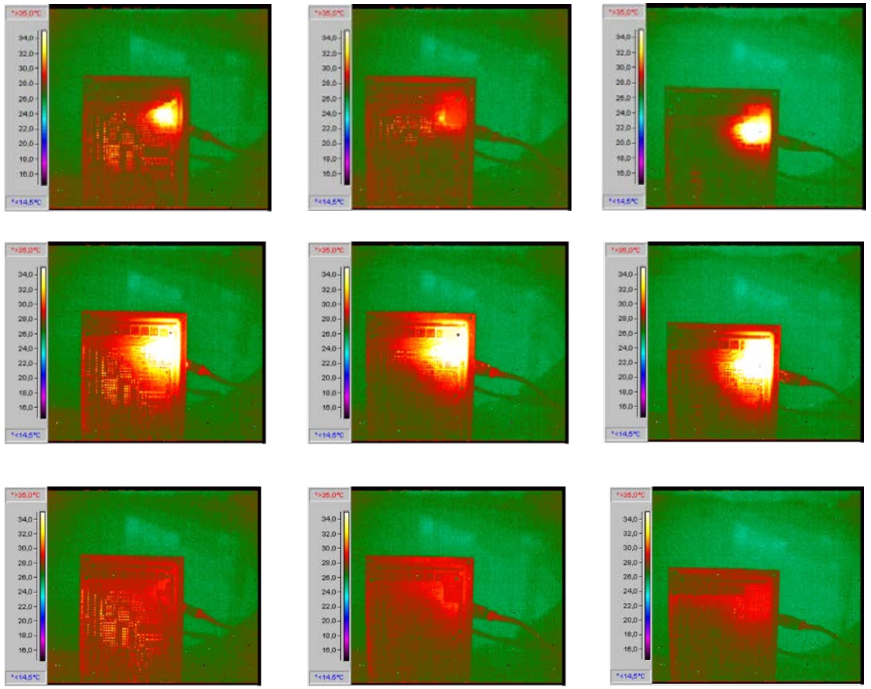


Thermal interface or heatsink paste printed



Heat transfer with a combination of thermal interface paste and heatsink

Comparing heat dissipation characteristics of heatsinks



PCB without heatsink

PCB with Cu-heatsink

PCB with printed heatsink paste

- **Heat-up phase**

  Measurement PCB surface after 1 min thermal load

- **Heating phase**

  Measurement PCB surface after 4 min thermal load

- **Cool down phase**

  Measurement PCB surface after 4 min heating and subsequent 4 min cooling down

Any Questions?

Thank you!