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Changeable Thermal Management for LED-Lighting

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Abstract

Thermal management of LED lights can be arranged by deliberately influencing lighting components conduction capabilities and reducing the thermal contact resistance for various joining processes. The research details the possibilities thereof and shows the thermal contact resistance of plastic and aluminum joining for different connection processes.

Introduction

Over the past couple of years, light emitting diode (LED) light sources have exploded onto the open market due to their energy saving potential and their continuous improvements in the color and luminosity and evenness of the light emitted. Retrofit lights, which possess a similar design to the common light bulb and are able to be screwed into standard lamps, have exponentially increasing sales figures in particular. Simultaneously, further breakthroughs in the overall LED efficiency are being made so that the aforementioned light sources are subject to changes in short cycles. Nevertheless, a versatile product and manufacturing process design is necessary in order to allow for a highly automated manufacturing process. The requirements placed on the light source’s thermal management change with the embedded LED-chips as well as the necessary power electronics. Consequently, this must also be designed to be properly versatile.

Thermal management, the management of heat dissipation from the LED into the surrounding environment, is of significant importance as it has an immense influence on luminous flux losses and thereby on the life span of the light source itself. Various materials and material combinations are being used for the heatsink. Plastics play here an important role due to their freedom in product design and their low manufacturing costs. A sound understanding of heat removal in plastics as well as the heat transfer between plastics and other materials is paramount to properly understanding the conduction processes required to simulate the behavior of entire lights. Goal of a current project of the Institute of Materials Engineering is to gather existing findings and necessary new achievements as a base for a changeable future product and process development.

Not only the filling materials added and their matrix connection play a role in thermoconductivity modification, but the processing has a significant influence as well since these materials often show a strong anisotropic behavior. The same goes for the thermal contact resistance (TCR). The TCR is vastly different depending the various joining method used, such as gluing, back injection, or simple clamping. Illustrated below are a few starting points for the thermal management and options for modifying thermal resistances for plastic components and plastic-aluminum composites.

Thermal Management

LED light sources convert a significantly higher percentage of energy into light compared to conventional light bulbs. Currently, the amount is around 30%, approximately six times that of the normal light bulb. Simultaneously, both light source types differ in the way they dispense energy loss into the environment. Light bulbs emit as such infrared rays into the environment. LEDs have a significantly lower working temperature and as such emit negligible values for warmth by means of radiation. The power loss of 70% is thereby dissipated in thermal conduction processes.

Heat dissipation is an essential factor since the LED life span is achieved depends greatly on the temperature at which it is being operated. Having one of the lights burn out entails replacing the entire fixture, especially for non-modularized light fixtures with a permanently installed LED system without the ability to remove them.

Figure 1 schematically shows the construction of an LED. Here, the arrows point to possible paths the heat can travel when being emitted outwards. Yet before a convective heat transfer between the bulb and the lower heatsink into the surrounding environment is possible, a row of conductive processes take place in and around different materials. Simplified, this system can be viewed as a combination of thermal resistors, which are connected analogous to electrical resistor, parallel, or in a row.

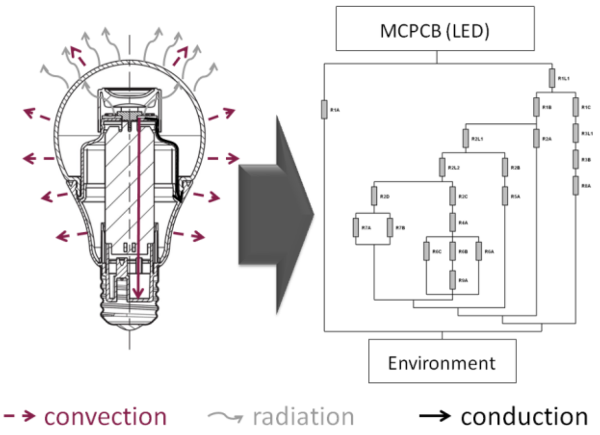

Figure 1. LED-Retrofit bulb modeled as combination of thermal resistors.

The regulation and, if necessary, the modification of these resistors is the main goal of thermal management. A more detailed overview which of the components of the LED-Light are involved in the thermal management gives Figure 2. Starting from the Metal Core Printed Circuit Board (MCPCB), which is carrying the LED itself, the heat is transferred to the upper heatsink, which leads it to the lower heatsinks. Due to achieving the necessary electrical safety regulations the lower heatsink is spread in an electrical conductive inner part and an electrically isolative outer part. These parts enable also a heat transfer to the bulb. The bulb and the lower outer heatsink define the surface, which can be used for a convectional transfer to the environment. Aside from the LED itself, there is another heat producing element in a LED light. The heat generated by the driver, which is the component to control the electrical power, can be lead out of the LED light via the lower heatsink as well as in direct conductive manner via the electrical conductors.

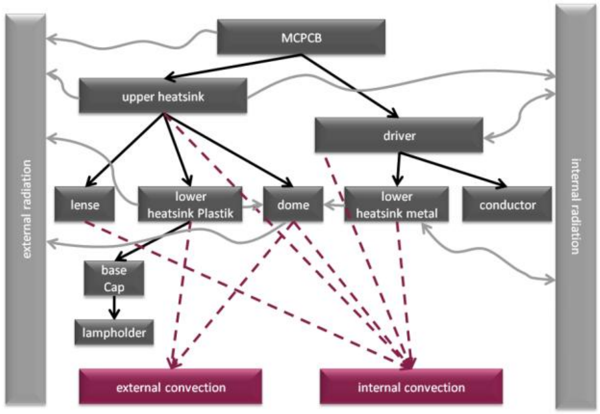

Figure 2. Thermal transport paths in a LED-Retrofit light.

Beneath a convective and conductive heat transfer to the environmental heat emanation also takes place. This effect can be neglected due to the relatively low temperatures around 80°C. The convective heat transfer depends on the surrounding fluid and its flow conditions. Hence the focus of the project is on conductive transfer. The modifications to heat conductivity inside the components and the heat transfer between various components will be distinguished below.

Heat Conductivity in Plastics

Thermal conductivity in plastics is based on the transfer of energy in the form of lattice waves referred to as phonons. Heat conductivity is possible both along the polymer chain through covalent bonds as well as between macromolecules via secondary valence bonds. The thermal resistance from the covalent bonds is however notably lower. [1,2] Based on this theory, several influencing effects on the thermal conductivity of plastic materials can be explained. For example, semicristalline polymers show a larger open path along the macromolecules due to their ordered structure. This usually leads to an improved heat conductivity compared to amorphous polymers.

Conductive Polymers

Polymers need to be modified with heat conducting filling materials to reach significant increases in polymer heat conductivity. In this case it is to be determined if the electrically insulating properties of the material are to remain or if the electrical conductivity is also acceptable or even wished. Electrically conductive variations commonly use graphite [3] or another carbon based filler such as carbon nanotubes [4,5]. Rare yet possible is the implementation of metallic fillers like copper or aluminum [6]. Electrically insulating compounds based on ceramic fillers are also available. The best characteristics are reached in this case by using boron nitride [7]. Yet, because of their comparably high costs, a multitude of further ceramic fillers such as aluminum oxide, magnesium oxide, titan dioxide, aluminum silicate, and many more are available. Combining carbon nanotubes and ceramic systems is yet a further possibility [8]. In addition to the selection and introduction of filler systems, the integration of these systems to the matrix material plays an important role. Improvements were made here through silanizating the filler materials [9].

Processing the filled materials in the injection molding process often sets an anisotropic behavior in terms of thermal conductivity. The thermal conductivity measured in flow direction (in plane) usually is higher than the one measured across the flow direction (through plane). This fact is already reflected in data sheets for appropriate materials. The in-plane as well as the through-plane values are both often found there. Unfortunately, this information did not suffice to predict the heat conductivity for concrete components. Regardless of the direction in the mold injection process, locally diverging filler orientations lead to differences in thermal conductivity. For further clarification, see Figure 3, which shows the heat conductivity of various materials depending on the measuring position. The thermal diffusivity both close to the gate and farther away were measured on a plate (170 mm x 60 mm x 1,8 mm) with a film gate. The measurement was carried out through-plane by means of square-shaped samples with a 25.4 mm edge length in the laser flash system LFA 467 from Netzsch. To calculate the thermal conductivity, additional values for the density and the specific heat capacity are needed.

These values were determined by using immersion method according to DIN EN ISO 1183-1 (density) and a DSC System (specific heat capacity). A polyamide 6 base material was tested (Ultramid B3 S, BASF). Aside from that, electrically insulating ceramics filled compounds with 50% and 85% fill ratio were tested (LATICONTHER 62 CEG/500-V0HF1, LATICONTHER 83 CP/85 from Lati S.p.A.).

The material with the lower fill ratio is based on a polyamide 6 matrix and contains underneath the ceramic fillers glass fibers as well. The Material with the higher fill ratio is based on a polyamide 12 matrix and contains just ceramic fillers. Furthermore, a graphite filled electrically conductive material (Therma-Tech NY 20GF-30GP from the company, Poly One) was tested. In this material, the composition is 30% graphite and 20% glass fiber. The latter can also be counted on fillers for improving the thermal conductivity due to its higher conductivity compared with thermoplastics with approximately 0.7 W / mK.

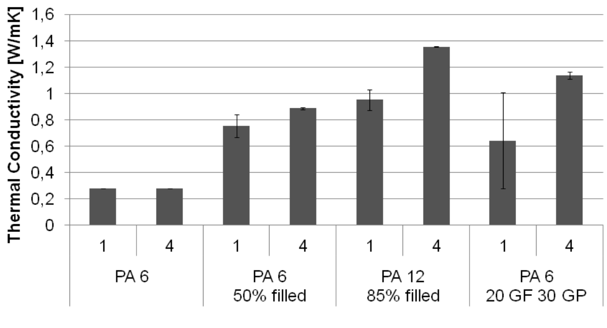

Figure 3. Influence of the variable measuring position (1=near the gate, 4=at the end of the flow path) on thermal conductivity.

It is apparent that while the base material displays no significant effects, the filled materials display an increase in the thermal conductivity along the flow path. This effect is strengthened with an increasing fill ratio or with the inclusion of filler materials with a stronger orientation, like as seen in the case with the electrically conductive material with a 20% fiberglass content. The differences occur based on the modified filler orientation on the flow path and are consistent with findings from other studies like [10]. Furthermore, it could be shown that a further increase in the effects is observable at a high fill grade of over 30%. The changes to the thermal conductivity from up to 42% make it quite clear that the influences of processing on the thermal resistance attributes for the individual components for a total light system cannot be left out of consideration. Strong fluctuations in the observable values along the flow path trajectory show that not only the component design but also the process design has an impact on the local thermal resistances of the individual components and as thus cannot be neglected when considering the overall thermal management of lights as well.

Interfacial resistance

The thermal contact resistances (TCR) arise between two materials or phases. Primarily two types of thermal transfers occur within the LED Retrofit lights. Both cases deal with the transfer of solid matter. The transition of metallic components, above all aluminum alloys, to polymer components and in between various polymers is an area of interest. If one takes thermal interface resistances into consideration so as to include established approaches to their explanation and prediction of different levels. There are macroscopic effects based on the boundary effect in interactions of macroscopic contact areas, microscopic effects, which consider mainly the surface properties of solids and film effects, which are considered based on forming the interfacial films.[11] Models, which describe the transition based on the theory of electric performance processes in solids are not directly usable for polymers. Notwithstanding, there are many investigations in the context of metal-metal interfaces, but it is questionable if these findings are fully transferable to plastic compounds and to how questionable it is whether the links are fully transferable to plastic compounds. Description approaches to transition from plastic to metal are found mainly in the form of studies on the TCR between melt and mold in injection molding. [12-15]

In order to get an overview in which size order the thermal contact resistors appear at the aforementioned joint techniques, view Figure 4. As can be seen in the aforementioned graphic, the combination of A1Mn1 plates (surface 380-625 mm^2, thickness 0,6 mm) with polyamide 6 (Ultramid B3 S). Listed here is the contact resistance of loosely-defined samples in which the degree of planarity is based on achievable results under realistic conditions. The values for bound samples placed under loose pressure is representative of low pressed connection types, such as the snap hook or clamp connection types. In these cases, the composites were placed under additional weight during the measurement. The weight used in this situation generated an overall force weight of around 300 Pascal. Conductive pastes are widely used in electronics to improve thermal transfer. In Figure 4, two such cases, in which the paste was implemented, are shown. First, a composite with a very thin layer of heat conducting paste is implemented. The paste does not lead to an increase in the overall composite thickness and as such allows for an automatic fit to the contours of the form when mounting. For the next case, a composite with a thicker heat conducting paste layer is used. The layer thickness in the second set is approximately 0,3 mm and leads to a measurable increase in the overall composite thickness and is as such not able to be implemented in a versatile thermal management. In both instances, the heat conducting paste (Revoltec Cooling with 10% silver compound) was used. The lower paste layer thickness allows for a direct contact to be established between the two components, specifically between aluminum and PA 6, as the heat conducting paste fills possible gaps. The preliminary contact between the two is variable with a higher layer thickness. Furthermore, the A1Mn1 plates were back injected in a hybrid injection process. The resulting compound is representative of the back injection of heatsinks and integrated component creation with LEDs. The values were determined using the laser flash method previously described. An integrated contact resistance calculation was used, which was however mainly due to the calculation of the contact resistance based on unknowns in a series circuit with two known, thermal resistances.

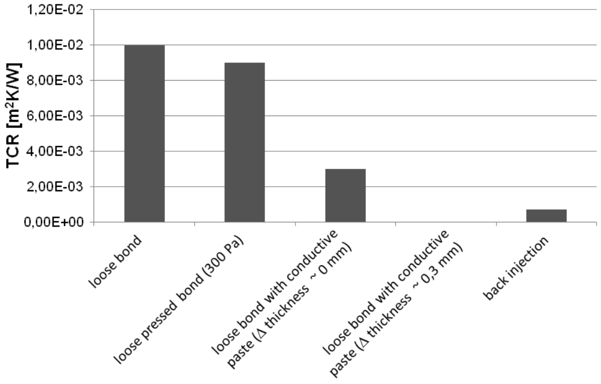

Figure 4. Influence of different bonding techniques on the TCR of PA 6 - AlMn1 compounds.

It is clear that loosely connected composites have a very large TCR. This value sinks, albeit minimally, however, when additional pressure is applied. This is based primarily on macroscopic contour differences. Using heat conducting paste as an in between layer evens this effect out somewhat, leading to a reduction in the TCR. In cases with the thin layer present, this was only noticeable partially on locations where there were significant contour differences.

As such, this means that the macroscopic and microscopic contour differences are smoothed out, yet microscopic differences in contour at the points of direct contact between the samples already exist when using a thicker layer of conductive paste to reduce macroscopic and microscopic based thermal resistances across the entire sample surface. Figure 5 illustrates these relations.

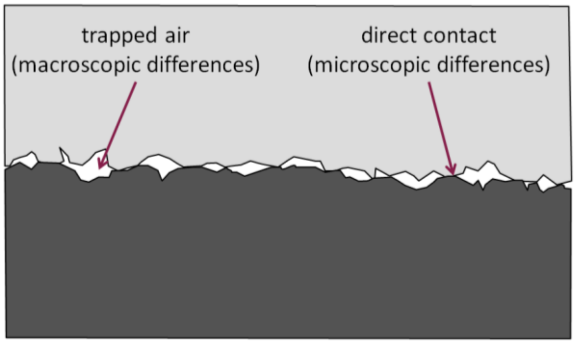

Figure 5. Sample schematic of macroscopic contour differences.

By directly back injecting the aluminum, no macroscopic contour deviations occur, consequently the volume of trapped air is near a minimum. Nevertheless, a complete molding of the surface microstructure cannot achieved, thus leads to the TCR as depicted.

Resulting Effects on the Thermal Management

In order to achieve a changeable thermal management for LEDs, a changeable product design as well as changeable process design are necessary. The former is achieved by using a modular principle for the individual components involved in the thermal management of LED lights. For a changeable process design, the degree of versatility must next be defined, as an eternally flexible solution presents no reasonable long term economic solution [16]. For this reason, it is necessary to define the useful potential processing techniques for thermal management in order to derive which processing and joining techniques represent a realistic process variation in the near future. These do not necessarily have to be absolutely reasonable from a purely economic perspective as per the current standard demanded. Once these are identified, the next point is focused on enabling the finished systems through a modularized construction and the ready interfaces for future accommodation.

The case observed here dealt with the currently usable materials. Currently, for example, aluminum components or their variants of thermal conductive polymers or standard plastics have to be mounted. On the other hand, variability must be implemented in regard to the connection techniques. With this in mind, process integrated methods, like the direct back injection of heatsinks or multiple component molding of electrically conductive and isolated plastics, are to be included as well.

Conclusion

It is possible to influence the thermal management through both the material as well as the process itself. The heat transfer inside a component is significantly determined by the orientation of the filler material and is thus able to be configured through adjusting the process parameters within certain boundaries. The TCR is able to be noticeably reduced through back injection compared to the loose joining techniques.

A life span of up to 10000 hours is striven for in certain bulb types. Further tests will show how the aging process affects the materials and connections, whereas hybrid composites and adhesive bonds also need to be observed.

Acknowledgements

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