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A Novel Approach for Reliability Investigation of LEDs on Molded Interconnect Devices Based on FE-Analysis Coupled to Injection Molding Simulation

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ABSTRACT Due to many advantages, such as cost-effective production, design freedom, and weight reduction, plastics have replaced metals and ceramics in many fields. However, engineering plastics are good thermal insulators. This characteristic, although beneficial in certain applications, poses many challenges in many heat-generating applications. This can lead to hot spots or even to an increase in the device temperature. Along with the increasing demand for plastics in areas of the lighting technology or in the automotive field due to the free shaping potential, the requirements are becoming more challenging. Driven by the trend of miniaturization, applications with high heat generation often have to operate in the tightest of spaces. Since not always sufficient space for complex cooling systems is given, the housing or the substrate should assume the task of thermal management. In regard to this fact, the use of thermally conductive thermoplastics seems to be very appealing. Quality loss, poorer reliability, loss of performance, and even failure can occur in case of insufficient heat dissipation. In order to improve the properties of these polymers, highly heat-conducting fillers are added in order to improve the thermal conductivity of the compound. Another technology trend that has been prevalent for years is the use of simulations. Due to shorter product life cycles and therefore shorter development times, simulation has become an indispensable part of the chain of product development. Time-consuming and costly test series make the simulation more and more important as a tool for material and product design. In this context, this paper presents a novel approach for reliability investigation and lifetime estimation, based on simulation. Therefore, a simulative method based on coupling the results from the process simulation (injection molding simulation) to finite element analysis was developed and explained. This coupled method makes it possible to take into account the manufacturing process and its engendered filler orientation. The obtained findings are compared to conventional thermal steady-state analysis and used in order to better predict the lifetime of LEDs mounted on thermoplastic substrates, the so-called molded interconnect devices. It is demonstrated that it is necessary to consider the filler orientation, especially in the case of 3D substrates.

INDEX TERMS Finite element analysis, FEA, process simulation, thermal analysis, steady-state analysis, injection molding, plastics, thermoplastics, filled plastics, filler, matrix, compound, light emitting diode, LED, molded interconnect device, MID, thermal management, reliability, Arrhenius, failure analysis, lifetime model.

I. INTRODUCTION

In order to identify any flaws of electronic assemblies as early as during the design phase, the use of simulation experiences steady growth. This is also of great interest to the molded interconnect devices technology (MID). This technology enables the simultaneous integration of mechanical (e.g. substrate by injection molding [1], [2]), electrical (e.g. electrical layout by laser direct structuring [3]) and thermal functions (e.g. heatsinks [4]–[6]). The application of

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simulation methods leads not only to an optimization of the variety of materials used during the production phases but also to a shortening of the process chain with a comparable cooling effect.

In terms of time and associated resources, finite element (FE) simulations are increasingly gaining in importance for MID applications in connection with accelerated environmental tests for reliability assessment [7]–[9]. Compared to the FR4 standard printed circuit board (PCB), the anisotropy of the thermoplastic substrates becomes more difficult to predict, which additionally depends on the filler orientation from the injection molding process, necessitating comprehensive material characterization, lifetime investigations and modeling.

In order to take into account the effects of the injection molding process and its resulting filler orientation, FE analyses have to be coupled to these corresponding process simulations. For this, material parameters must be correlated to temperature, filler properties (e.g. orientation, aspect ratio, degree of filling…), and the material models required for calculations must be created. Studies dealing with micromodeling of representative volume elements (RVE) based on the finite-element-homogenization method (FEH) and taking into account the interaction between different neighboring filler particles can be found in [10]. This approach is beneficial to study percolation effects, interferences between fillers and their microscopic impact on the thermal conductivity inside of this RVE. However, the resulting findings concern only the properties of this representative element and no statement can be made about the complete overall part or substrate, since the filler orientation varies within the part. This limits the ability to study the effects of the boundary conditions (convection and radiation), the geometry and the interaction between devices mounted on this part.

Works based on the mean-field homogenization method (MFH) in order to consider the filler orientation in the macromaterial, which will be investigated in the FE analysis, have also been conducted [7]. In this case, the results of injection molding simulation were coupled to a structural mechanical FEM analysis. It was demonstrated how valuable it is to consider this engendered anisotropy on the coefficient of thermal expansion and the caused mismatch between substrate and device. This effect is crucial for the reliability of solder joints and has to be modeled as precise as possible.

By contrast, reliability investigations based on thermal FE analysis taking into account the manufacturing process of the substrate and its triggered effects, by creating a macromaterial model with mean field homogenization, were not explored yet. In order to be able to provide quantitative reliability predictions based on such a simulation approach for electronic components (e.g. surface mount devices SMD) assembled on MID, mathematical lifetime models have to be set up. In previous works [3], [11], a deep and detailed reliability investigation of LEDs mounted on MIDs was presented in accordance with the IES LM-80-08 test standard, the IES TM-21-11 estimation method [12] and the JEDEC and EIAJ standards [3], [13]–[16]. The choice of LED as an application example is due to the well-known and already proven dependence of its lifetime on the thermal performance of the substrate, it is mounted on. Reliability investigations of LEDs were already discussed in [17]–[29]. Thus, the influence of the MID substrate choice on the long-term performance of the LED was discussed. Moreover, the impact of the forward current and of the ambient temperature on the junction temperature of the LED and consequently on its reliability was examined. After analyzing the occurred failure mechanisms, by means of X-ray analysis, thermal transient testing and microscopy, a resulting lifetime model with very good fitting quality was presented and discussed.

This model describes the relationship between the characteristic lifetime LT and the real junction temperature T_j measured for different constellations under different operating conditions. This was conducted using an infrared thermographic camera and transient thermal methods (measurement of the thermal resistance R_{thj-s} between junction and solder joint) in order to obtain the correct temperature at the junction. Nevertheless, it is advantageous to predict this temperature using simulation, in order to optimize and minimize experimental effort and cost and to pretest different interesting design rules.

This paper presents a novel approach to predict the lifetime of electronic devices, in general, and of LEDs as a special case. This model is based on thermal FE analysis coupled to injection molding simulation in order to take into account the filler orientation and the resulting anisotropy of the thermoplastic substrate.

In what follows, section II gives an overview about the tests and methods implemented and used in this work. It begins with a general description of the proposed approach. After defining the design of experiments and the boundary conditions, a detailed description of workflow of the coupled simulation procedure is presented. The results of the benchmark between the different methods are illustrated and discussed in section III. Conclusions are presented in section IV.

II. TESTS AND METHODS

A. APPROACH AND DESIGN OF EXPERIMENTS

The computer-aided design of reliable microsystems and electronic components can significantly reduce the cost of product development and testing. For this reason, the finite element method (FEM) is widely used, for example, to predict the thermal performance of electronic components. The theoretical analysis of the thermal performance of assemblies under different operating conditions includes the definition of the boundary conditions, the characterization of the materials as well as sound knowledge of possible failure mechanisms. In order to be able to determine the reliability of electronic assemblies with sufficient precision from the results of finite element analysis (FEA), the challenge lies in the creation of adequate geometry models, the consideration of correct material properties, the exact specification of the boundary conditions and the use of mathematical life models such as

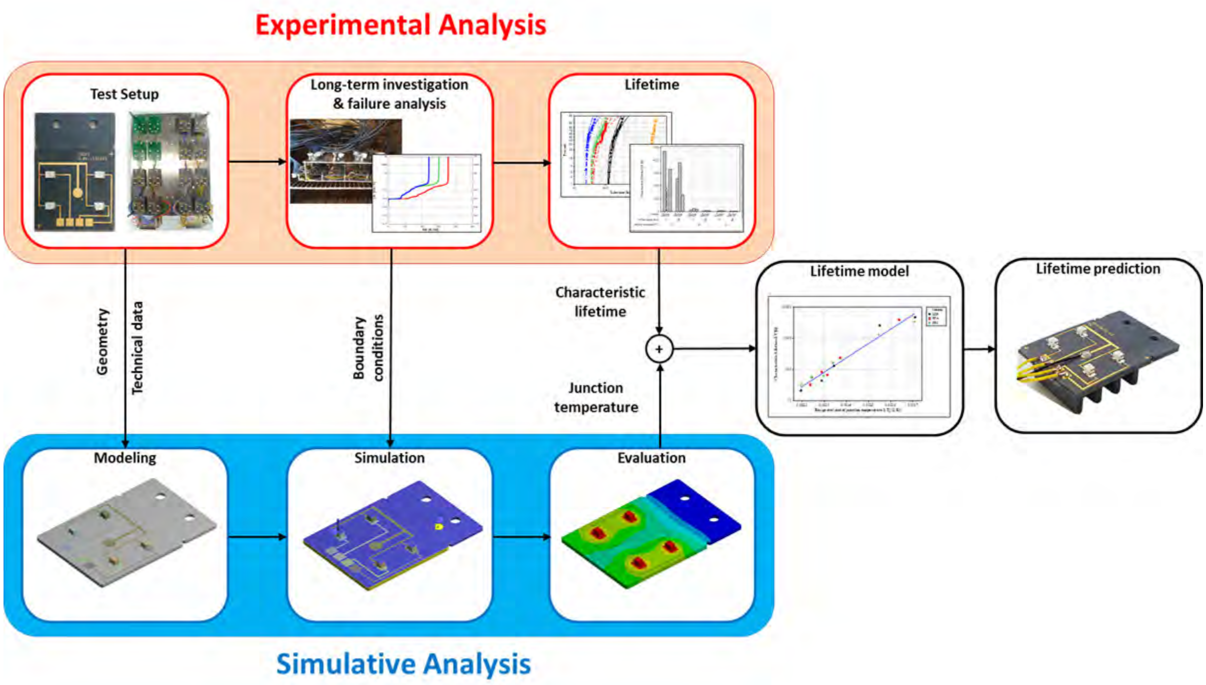

FIGURE 1. The approach for the reliability investigation based on experimental and simulative analyses to predict the lifetime on more complex geometries.

the Arrhenius equation [30]. Based on such lifetime models, weak areas and deficiencies can be identified during the development phase and even before the experimental tests, and the lifetime of devices can be predicted.

In this context, the lifetime model developed in previous works [3], [11], describes the relationship between the initial junction temperature and the characteristic lifetime of the LED. Therefore, the LEDs were tested under different ambient temperatures (25 °C, 85 °C, 105 °C) and were subject to two different forward current levels (75 mA, 100 mA). This LED features a dominant wavelength equal to 470 nm (blue), has a viewing angle of 120ř and a maximum forward current of 25 mA. Typical forward voltage value is 3.2 V across a current of 20 mA (64 mW electrical power). The tests were conducted on two different MID substrates (LCP and PPA based materials), with different thermal conductivities, and on a standard FR4 printed circuit board (PCB) as a reference. The geometry chosen for the substrate was a planar plate. In this work and for the sake of simplification, it will be referred to this geometry as ''2D''. After conducting failure analysis and statistical distribution tests, the characteristic lifetime could be determined. For the determination of the junction temperature values, thermography and thermal transient measurements had to be carried out [3], [29], [31], [32]. For this purpose, an infrared camera was used to measure the solder joint temperature (at equilibrium, steady state) on the thermally active side of the LED and the transient measurement technique (using a t3ster system from Mentor graphics) was used to determine the thermal resistance R_{thj-s} between the junction and the solder joint. The description of this measurement procedure can be found in a previous publication [3]. In this manuscript, the focus is on the simulation approach and all the presented results refer to the steady state, with and without consideration of the filler orientation. The experimental data seemed to follow a model based on the following Arrhenius equation,

$$LT = C_T \cdot e^{E_A/k \cdot T_j} \tag{1}$$

very well where, LT is the characteristic lifetime, $C_T = 2 \cdot 10^{-9}$ is the thermal factor, $E_A = 0.91$ eV is the activation energy, $k = 8.617385 \cdot 10^{-5}$ eV·K^{-1} is the Boltzmann constant and T_j is the initial junction temperature in Kelvin. The activation energy E_A of LEDs typically ranges from 0.1 eV to 0.9 eV [28], [33]. In order to make use of this model to predict the lifetime of LEDs tested under different operating conditions or mounted on other substrates (material and/or geometry), it would be advantageous to benefit from FE analysis to calculate the engendered heat and, consequently, the junction temperature. On this basis and in regard to this presented model, the characteristic lifetime can be determined using simulations.

Fig. 1 illustrates the proposed approach for the reliability investigation based on experimental and simulative analyses, which can be used to predict the lifetime of electronic components, in general, on more complex geometries. In this study, the heatsink geometry, shown in Fig. 2 and referred to as ''3D'', was chosen for investigation. The full factorial design of experiments is illustrated in Table 1, where all the

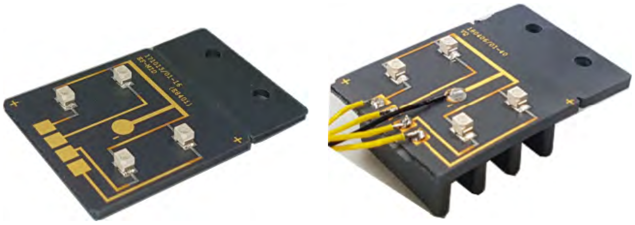

FIGURE 2. **The two considered substrate geometries. Left: Planar plate 52 mm × 37 mm × 1.5 mm (2D) Right: Heatsink substrate (3D) Plate 52 mm × 37 mm × 1.5 mm Ribs 30 mm × 8 mm × 3 mm.**

TABLE 1. **Full factorial Design of Experiments (DoE) relevant factors and their corresponding stages.**

Factor	Stage low	Stage high
Forward current	75 mA	100 mA
Ambient Temperature	85°C	105°C

relevant factors and their corresponding stages are presented. The LEDs mounted on 3D heatsinks are tested under forward currents of 75 mA and 100 mA and by ambient temperatures of 85 °C and 105 °C. These heatsinks are made of LCP (liquid crystal polymer) based thermoplastics, which are filled with talc plates. The characteristic lifetime was determined as explained in the previous studies [3], [11] and the junction temperature was evaluated by two different simulation procedures. The first way, which is the most common and straightforward way, is to conduct a steady state thermal analysis (e.g. with Ansys Workbench). However, this kind of analysis does not take into account the effects caused by the injection molding process and its impact on the anisotropy. This kind of procedure and its steps (geometry, meshing, boundary conditions, etc.) was already explained in previous works [1], [2]. In this manuscript, the focus lies on the second procedure, with respect to the triggered fiber orientation, which will be addressed in the next subsection. A benchmarking between both procedures is also presented in the next section.

B. COUPLED SIMULATION PROCEDURE

Different forces and moments act on the fillers due to the velocity gradients within the melt flow, causing filler orientation and hence anisotropy. Simplistic models are based on the assumption that, due to the velocity gradient from the center of the cavity to its wall, rotational forces act on the fillers, causing them to rotate about their transverse axis until an equilibrium is met or until the fillers are oriented in the flow direction. The flow velocities in the center of the cavity are approximately constant, which is why a filler orientation results here only due to transverse and elongation flows and therefore the fillers are oriented predominantly perpendicular to the flow direction.

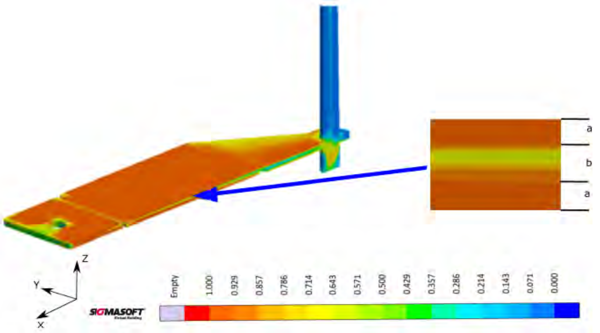

FIGURE 3. **Injection molding simulation of the test substrates (2D), filler orientation in the x-direction.**

Consequently, in injection molded parts made of filled plastics, a characteristic layer structure comes into play, as it can be seen in Fig. 3. The simplest model consists of a 3-layer structure (a, b, a). Fillers near to the wall of the cavity are mainly oriented in the flow direction (x-direction), whereas fillers in the center of the cavity are mostly oriented in the flow plane (x-z plane), as they are not subject to forced orientation (randomized orientation distribution). In other works [34], [35], 5-, 7- and multilayer structures can be found. The direction-dependent properties should be taken in consideration in the calculations and the simulations in the context of product development. In the scientific literature as well as in product datasheets, a thermal conductivity in the flow direction and / or perpendicular to it is occasionally indicated. This directional dependence is usually not taken into account in the standardization of the specimens, the procedure for the characteristic data measurement and, consequently, in the data specification in datasheets.

For these reasons, thermal conductivity has to be measured on the considered molded part. A common and well-known method for the determination of this thermal characteristic is the "Laser Flash Analysis" (LFA), whereby an energy pulse is emitted onto one side of the specimen. On the other side, an IR sensor detects the temperature rise. This method is described deeper in a previous work [1].

The groundwork for the MIDs considered in this work consists of thermoplastic materials (substrates). In order to be able to consider their anisotropy in the simulation, various simulation procedures are available. The simplest alternative is to consider the material property of the overall composite, in this case the thermal conductivity, to enter it directly into the FE simulation software and assign the directional dependence to the geometry models by using the global coordinate system. This simulation procedure is typically used for thermal simulations of planar boards. The behavior of complex three-dimensional polymer parts under thermal boundary conditions can no longer be described, in a sufficiently accurate way, with this simulation procedure, since the effects of the manufacturing process are not taken into account. In the case of filled polymers, the injection molding process influences the microstructure of the material and,

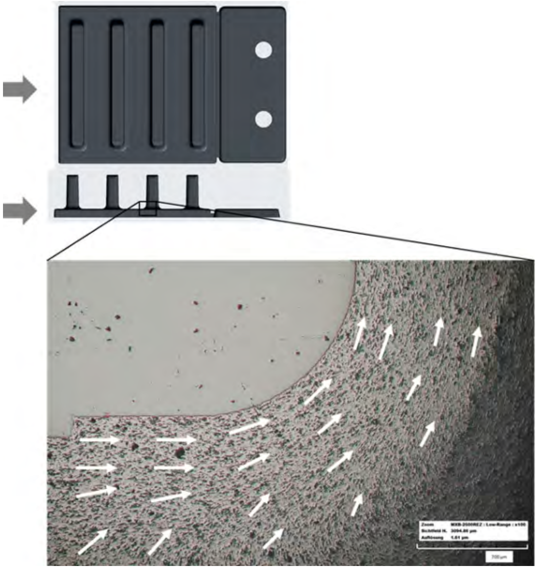

FIGURE 4. Filler orientation in the ribs of the heatsink substrate (3D).

TABLE 2. Parameters for the injection molding simulation.

Parameter	Value
Maximum volume flow rate	25 cm^3/s
Initial mold temperature	105°C
Initial melt temperature	335°C

thus, the subsequent behavior under thermal load. The filler orientation leads to significant variations of the local material properties as well as of the anisotropic behavior. The cross section prepared from the heatsink substrate (Fig. 4) illustrates the filler orientation in the ribs.

A realistic simulation must, therefore, consider the manufacturing process, derive the resulting material properties and then transfer them to the part. For this reason, coupled simulations between injection molding simulation and FE analysis have to be implemented. The simulation tools used in this work were SIGMASOFT® for the injection molding simulation, ANSYS® as a finite element analysis tool and digimat® for the coupling. Already during the production of the molded parts, injection parameters such as volume flow over the injection time, temperature of the melt and of the cavity were recorded. In accordance with the injection molding protocols, process simulations were carried out. Some of the main injection parameters, implemented in the simulation, are summarized in Table 2. Fig. 5 shows very good agreement between the flow simulation and the filling study.

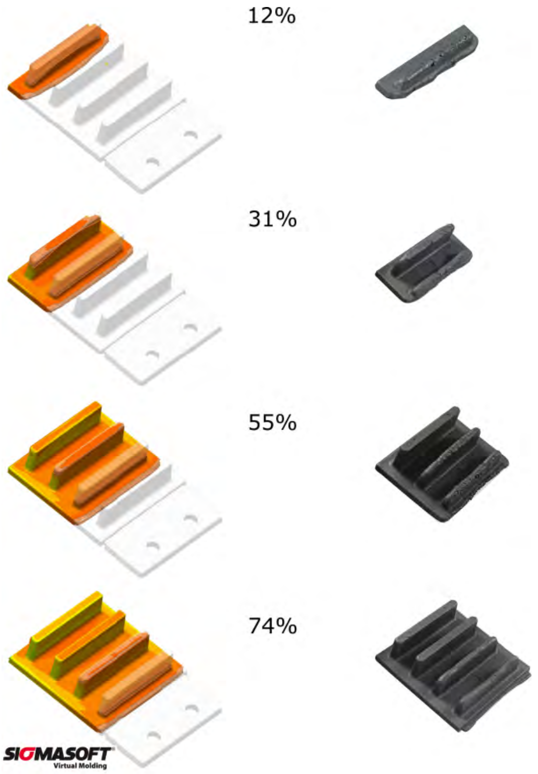

FIGURE 5. Comparison between simulative (left) and experimental (right) filling studies by different filling levels.

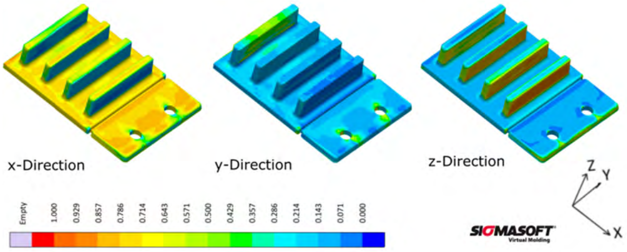

FIGURE 6. Filler orientation in different directions based on the injection molding simulation.

According to this filling behavior, most of the fillers in the ground plate are oriented in the flow direction (the x-direction of the global coordinate system). However, the fillers in the ribs are mostly oriented in the z-direction, which is also the flow direction in this area of the part (Fig. 6). Subsequently and in contrast to the ground plate, the thermal conductivity in the ribs is higher in the z-direction than in the x-direction, since the fillers are in particular responsible for the heat conduction.

Thanks to the software digimat®, the injection molding process is taken into account in the FE analysis via an anisotropic material description (material model). These material models have been created by reverse engineering using the software module digimat®-MF [36]. This step has to be conducted on the geometries of the test samples prepared for the LFA measurements. The preparation of these samples was described in a previous work [1].

There are three approaches to calculate the thermal conductivity of filled plastics: analytical models, mean field homogenization (MFH), and finite element homogenization (FEH) [10]. In the present work and as mentioned before, only the MFH approach is applied in order to consider the filler orientation in the macro-material, not only in the representative volume element (RVE) as it is the case of the FEH approach.

Heterogeneous materials are subdivided into matrix and fillers (inclusions). The matrix itself is considered to be homogeneous, and the fillers can be present in different geometries (spheres, fibers, plates, etc...). The MFH makes it possible to make predictions about the influence of the microstructure on the macroscopic properties. On the microscopic level, the RVE is also defined. This representative element corresponds to the statistically average structural properties. The RVE contains the matrix component and the embedded filler particles with their specific and corresponding properties. At the macroscopic level, each material point is the center of such an RVE. Under certain boundary conditions, the properties of the matrix and inclusions are calculated for the RVE and then, by means of micro-macro transition, issued as volume averages. The homogenization calculates a volume averaged thermal conductivity of the RVE. The heterogeneous and homogeneous materials now have the same effective thermal conductivity [36].

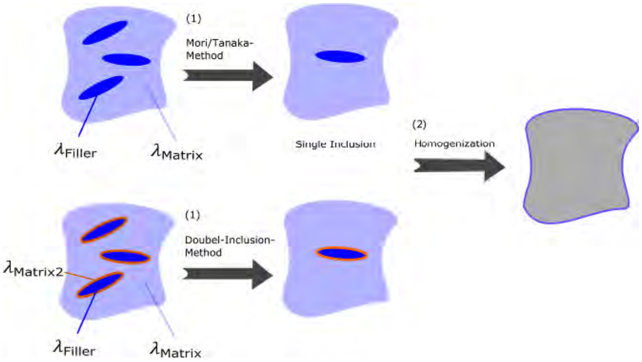

FIGURE 7. **Comparison between the Mori-Tanaka and the double-inclusion homogenization approaches (according to [26]).**

In the following, the Mori-Tanaka and the double-inclusion approaches will be described. Mori-Tanaka's method approximates the interaction between the phases. This model assumes that each inclusion has the same properties and is embedded in a matrix. This matrix is subject to average load [37]. Fig. 7 shows in the upper part the principle of the Mori-Tanaka approach. In theory, this method is limited only to filler contents of 25% (volume fraction), which is the case of the material investigated in this work (about 25.3% vol.-%). In practice, good predictions can be made even at higher filling levels [36]. Another limiting assumption of the Mori-Tanaka model is that all inclusions should have the same properties and thus only a two-phase mixture exists. Multiphase systems (>2 phases) can be approximated using the double-inclusion method [38]. The basic idea is that each inclusion is surrounded by another layer and that it is embedded in the matrix itself. Fig. 7 shows the double-inclusion method compared to the Mori-Tanaka approach. In this work, the Mori-Tanaka approach was utilized to consider the 2 phases available. Typically, the mean field homogenization considers thermo-mechanical studies. For thermal modeling, Hatta and Taya have developed an analogy to the mechanical method [39]:

Stress σ ↔ heat flux q
Strain ε ↔ temperature gradient ΔT
Stiffness C ↔ thermal conductivity λ.

Thus, mean field homogenization can be used to calculate thermal conductivity of multiphase materials.

As mentioned before, digimat is the material modeling software used in this work. It allows the prediction of the constitutive behavior of heterogeneous and / or anisotropic materials such as filled plastics. In the present study the software module digimat-MF was utilized. This module applies the mean field homogenization to calculate the thermal properties of the compound, depending on its microstructure morphology (inclusion shape, orientation, filler fraction, filler aspect ratio, etc...).

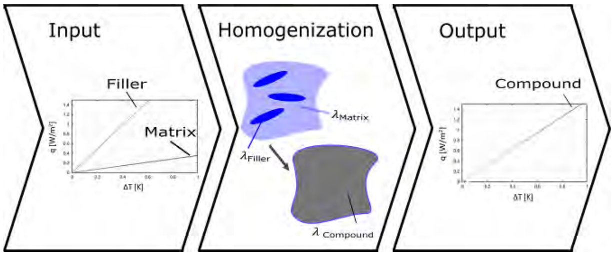

FIGURE 8. **The workflow of the material modeling using digimat-MF.**

In digimat, the individual materials are first defined in terms of properties relevant for thermal analysis, in detail the density, the specific heat capacity and the thermal conductivity. In the next step, one of the created materials is assigned to the phases present in the thermoplastic material and the proportion of the phase is then stated as volume or mass fraction. In the phase, which is assigned as an inclusion, the aspect ratio and an orientation tensor, which represents the normalized fiber orientation obtained from the injection molding simulation, can additionally be specified. Finally, a load (heat flux) is allocated to the RVE. When performing the analysis, the load is applied and the temperature response is calculated. The slope of the resulting curve corresponds to the thermal conductivity, according to Fourier's law [40]. Fig. 8 shows the basic scheme of material modeling with digimat-MF. In order to create the best possible material model, a "reverse engineering" step has to be carried out. The aim of this process is an adjustment and a comparison between the results of the material modeling and the measurement results, e.g. from the laser flash analysis. Fig. 9 shows the results of the reverse engineering for the considered material. As it can be seen in these plots, a very good match between the LFA measurements and the material modeling

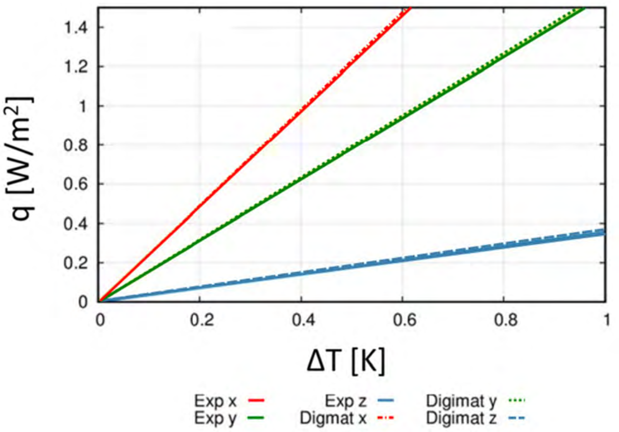

FIGURE 9. The results of the reverse engineering step conducted on the considered material. Heat flux vs. temperature gradient.

could be achieved (superimposed curves for each direction). Both the LFA measurements (marked as "Exp" in the figure) and the material modeling (labeled "Digimat" in the figure) were performed for each direction.

When coupling injection molding simulation with FE analysis, it should be kept in mind that meshing properties, needed in both simulation steps, differ from one another. The information from the injection simulation (fiber orientation, stress conditions, temperature) must therefore be mapped on the mesh used in FE simulation. This is done via the software module digimat® -MAP and is shown schematically for the heatsink substrates used in this work in Fig. 10.

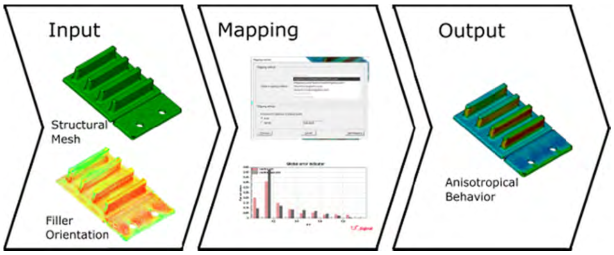

FIGURE 10. The workflow of the properties mapping on the FE mesh using digimat-MAP.

In order to establish an integrative procedure for thermal simulation of thermally conductive plastics, experimental analysis is needed. Not only coupling-required parameters, such as thermal conductivity, have to be determined, but also boundary conditions (e.g. heat transfer coefficient for the convection or the emissivity for the radiation [1]) have to be considered in the steady state FE analysis. Fig. 11 summarizes the procedure for the proposed integrative simulation with process-dependent local anisotropic material properties. The resulting findings, in this case the junction temperature of the LED, can then be used in the lifetime model.

III. RESULTS AND DISCUSSION

First, in order to validate the simulation results, measured and simulation based junction temperature values of LEDs mounted on planar substrates (2D) were compared, as it can be seen in Fig. 12.

These presented results not only confirm the accuracy of both models (with and without coupling) in case of planar substrates, but also show that higher temperature values (conservative prediction) are predicted for all the considered constellations.

In order to investigate the improvement resulted from the use of the heatsink substrates (3D) instead of the planar substrates (2D), a comparison between experimental characteristic lifetime values of LEDs mounted on these different geometry substrates was conducted. As it can be seen in Fig. 13, the utilization of the heatsinks leads to amelioration for each and every constellation. For example, in the case of LEDs tested by an ambient temperature of 85 °C and a forward current of 75 mA, the characteristic lifetime increases from circa 131 h on 2D substrates to reach circa 480 h on 3D heatsinks, which corresponds to an increase of almost 3.7 times.

Fig. 14 presents the different lifetime models developed in this and in previous works. The black curve and the black dots illustrate the lifetime model ("MM" for measurement model) proposed in the previous work [3], where LEDs were tested on different materials (planar substrates) and under different operating conditions as explained in Section 2. Thereby, both characteristic lifetime and junction temperature were determined experimentally. In the case of the red dots, the junction temperature for the same constellations was calculated based on a steady state thermal analysis with no direct coupling with the injection molding simulation ("SM_2D_without_Coupling" for simulation model in case of planar substrates with no direct consideration of the filler orientation). In the case of these planar substrates, the good match between both models and their high determination coefficients R^2(0.963 for "MM" and 0.946 for "SM_2D_without_Coupling"), confirm that this simpler simulation procedure (in comparison to the coupled procedure) is fully sufficient. However, it should be underlined that orthotropic values of thermal conductivity, measured by LFA on the same substrates, were implemented. Using isotropic values or data from datasheets would not be adequate enough to achieve such a good matching [1]. Fig. 15 shows the standardized characteristic lifetime values determined in the experiment together with the standardized characteristic lifetime values predicted according to the Arrhenius relationship. For this purpose, the calculated junction temperature in the "SM_2D_without_Coupling" was utilized in the Arrhenius equation (Eq. 1). The standardization relates to the largest value of the characteristic lifetime (circa 4697 h) got from the experiment. This was the case of LEDs mounted on LCP based substrate and tested at 25 °C and 75 mA. The diagonal line corresponds to the ideal lifetime prediction. If the points are to the left of the diagonal line, the prediction is conservative. This means that the model predicts a shorter lifetime than the experimental one, which is a positive aspect in the field of simulation. If the points are

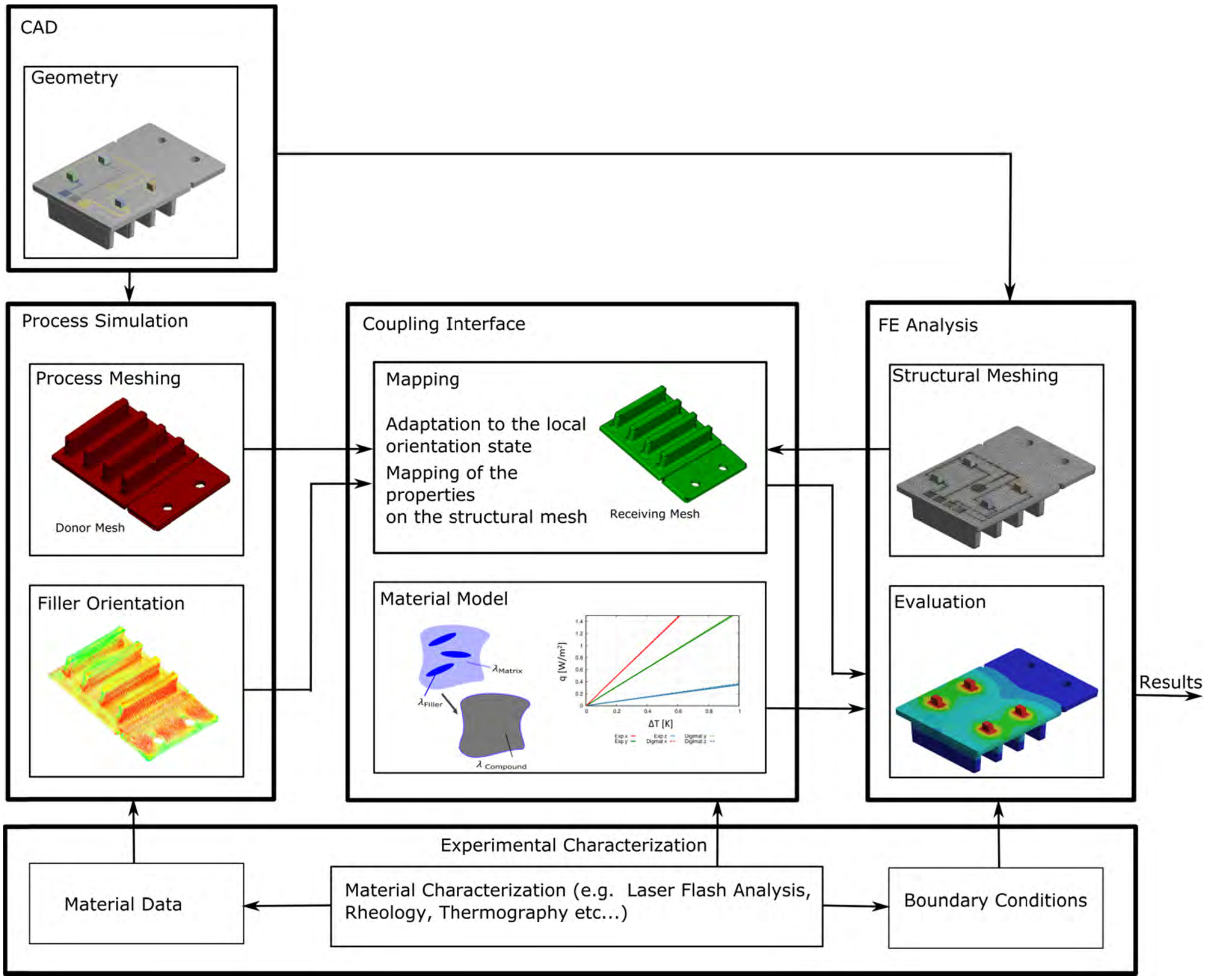

FIGURE 11. Procedure for integrative simulation with process-dependent local anisotropic material properties. Coupling of finite element analysis with injection molding simulation based on material modeling.

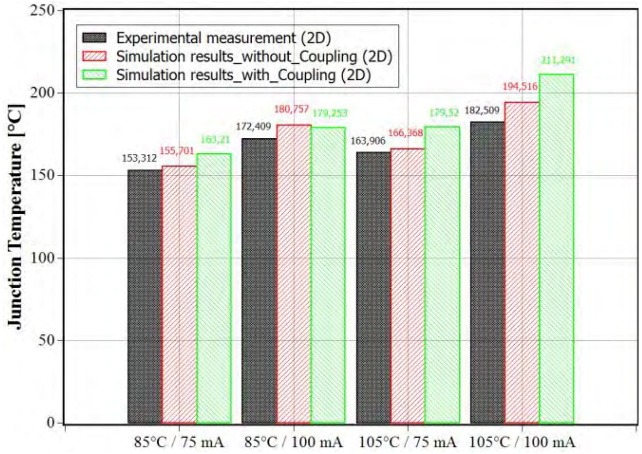

FIGURE 12. Comparison between measured and simulation based junction temperature values of LEDs mounted on planar substrates (2D).

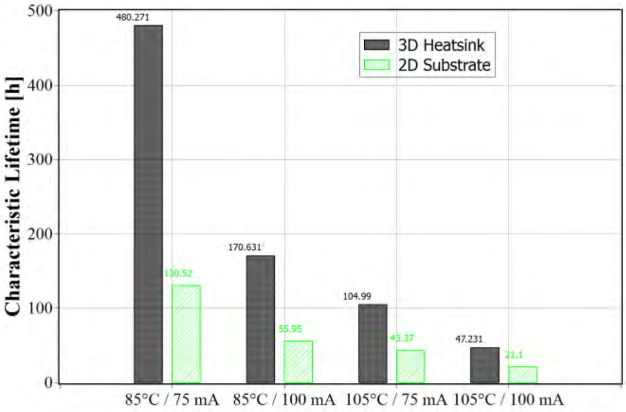

FIGURE 13. Comparison between characteristic lifetime of LEDs mounted on 2D substrates or on 3D Heatsinks.

to the right of the diagonal line, the model predicts a longer lifetime. It is then an optimistic prediction, which is negative in regard of product development and warranty. The closer the points are to the diagonal line, the better the simulation based prediction is. Fig. 15 confirms the good and conservative (positive) prediction of the "SM_2D_without_Coupling" model for LEDs on planar substrates.

Back to Fig. 14, the green dots present the lifetime model based on calculated junction temperature values (steady state

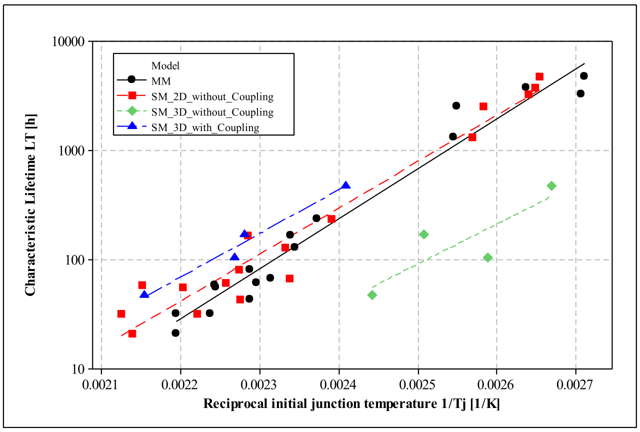

FIGURE 14. Lifetime models describing the relationship between characteristic lifetime and junction temperature. MM: Measurement model based on measured junction temperature values. SM: Simulation models based on calculated junction temperature values.

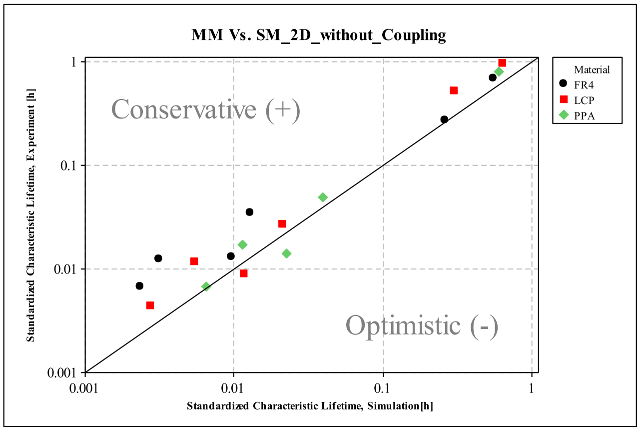

FIGURE 15. Standardized characteristic lifetimes determined in experiment vs. standardized characteristic lifetimes based on the junction temperature of model "SM_2D_without_Coupling".

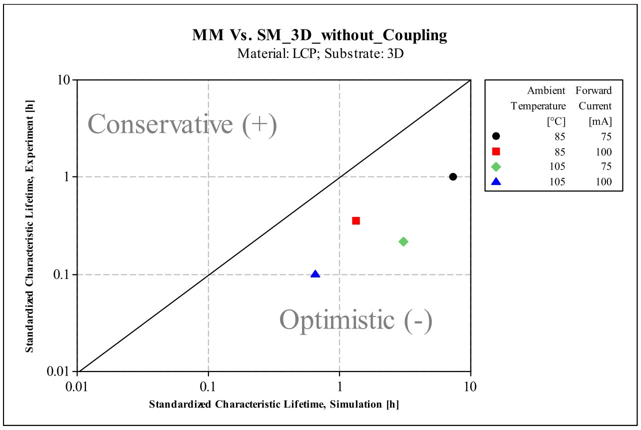

FIGURE 16. Standardized characteristic lifetimes determined in experiment vs. standardized characteristic lifetimes based on the junction temperature of model "SM_3D_without_Coupling".

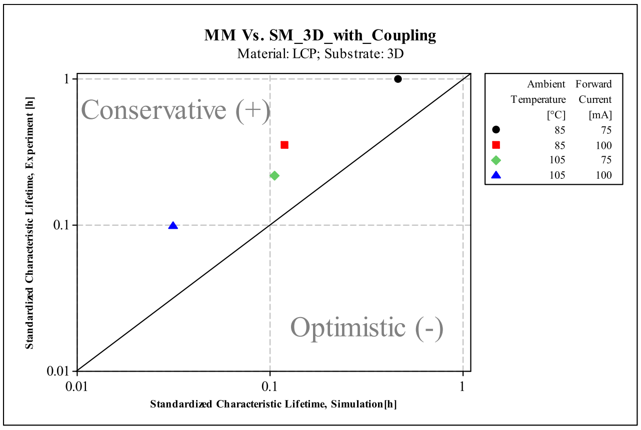

FIGURE 17. Standardized characteristic lifetimes determined in experiment vs. standardized characteristic lifetimes based on the junction temperature of model "SM_3D_with_Coupling".

thermal analysis) with no direct consideration of the manufacturing process ("SM_3D_without_Coupling" for the simulation model in case of heatsink substrates with no direct consideration of the filler orientation). In addition to the poor determination coefficient R^2 (0.732), the large spacing between these dots and the Arrhenius curve emphasize the fact that the injection molding process has to be considered in order to estimate the thermal behavior of more complex "3D" geometries.

Fig. 16 shows the standardized characteristic lifetime values determined in the experiment together with the standardized characteristic lifetime values predicted according to the Arrhenius relationship. For this purpose, the calculated junction temperature in the "SM_3D_without_Coupling" was inserted in the Arrhenius equation (Eq. 1). The standardization relates to the largest value of the characteristic lifetime (circa 480 h) obtained from the experimental investigation of LEDs mounted on the heatsink substrates. This was the case of LEDs mounted on the LCP based heatsink substrate and tested at 85 °C and 75 mA. This figure confirms the poor and optimistic (negative) prediction of the "SM_3D_without_Coupling" model for LEDs on heatsink substrates.

Fig. 14 contains also the lifetime model (blue dots) based on calculated junction temperature values taken from the coupled simulation procedure explained in Subsection 2.B. with direct consideration of the manufacturing process ("SM_3D_with_Coupling" for simulation model in case of heatsink substrates with direct consideration of the filler orientation imported from the injection molding simulation). The large determination coefficient R^2 (0.974) and the proximity to the Arrhenius curve obtained from experimental data confirm again the need to consider the injection molding process in the simulation procedure for complex geometries.

Fig. 17 shows the standardized characteristic lifetime values determined in the experiment together with the standardized characteristic lifetime values predicted according to the Arrhenius relationship. For this purpose, the calculated junction temperature in the "SM_3D_with_Coupling"

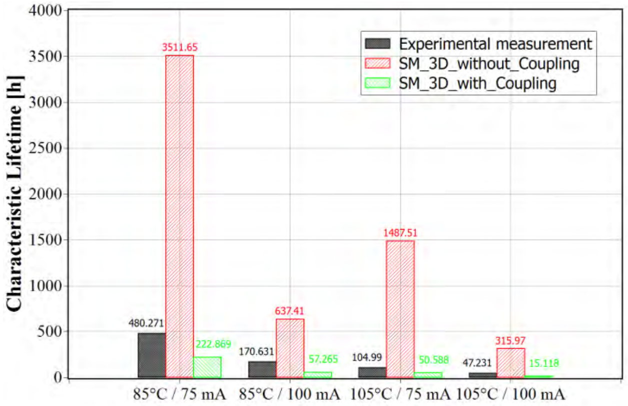

FIGURE 18. Comparison between measured and calculated characteristic lifetime values predicted by both proposed models and based on the Arrhenius equation Eq. (1).

was inserted in the Arrhenius equation (Eq. 1). The standardization relates to the largest value of the characteristic lifetime (circa 480 h) obtained from the experimental investigation of LEDs mounted on the heatsink substrates. This was the case of LEDs mounted on the LCP based heatsink substrate and tested at 85 °C and 75 mA. This figure attests the good and conservative (positive) prediction of the "SM_3D_with_Coupling" model for LEDs on heatsink substrates. A comparison between measured and calculated characteristic lifetime values predicted by both proposed models and based on the Arrhenius equation Eq. (1) is presented in Fig. 18. For example, in the case of LEDs tested by an ambient temperature of 85 °C and a forward current of 75 mA, the characteristic lifetime, predicted based on the junction temperature calculated without coupling of the process simulation results to the FE analysis, was 7.3 times higher than the measured values. This emphasizes again the effect of the manufacturing process on the thermal performance and how crucial it is to take into account the resulting filler orientation in the FE analysis.

IV. CONCLUSION

Simulation is opening new perspectives for reliability investigations, by better predicting the behavior of electronic components and/or packages. However, it is necessary to consider realistic boundary conditions and material parameters, especially in the case of filled plastics. Measurement techniques, such as the laser flash method, improve the quality of the simulation models. But, more complex geometries and shapes require consideration of the filler orientation, engendered by the injection molding process.

In this light, a novel approach for reliability investigation and lifetime estimation, based on simulation, was proposed in this work. Hence, a simulation procedure based on coupling the results from process simulation (filler orientation) to steady state finite element analysis by creating a material model (in this study by using Mori-Tanaka homogenization approach) was presented. By means of this coupled procedure, it was feasible to take the manufacturing process and its resulting filler orientation into consideration. A benchmarking with conventional thermal steady state analysis without consideration of filler orientation was carried out, relating to the lifetime prediction of LEDs mounted on filled thermoplastic substrates. It was demonstrated that it is advisable to conduct this procedure, particularly in case of 3D shapes. Otherwise, the lifetime values, predicted by the FE simulation without coupling, are too optimistic (up to 7.3 times higher than the measured values), and consequently not trustworthy.

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