Dynamics of moisture ingress in first and second level electronic housings

Helene CONSEIL[1], Gerald HAMM[2], Lutz MUELLER[2], Mathias HAIN[2], Rajan AMBAT[1]

[1] Materials and Surface Engineering, Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark
[2] Robert Bosch GmbH, Automotive Electronics, Tübinger Str. 123, DE-72762 Reutlingen, Germany

Abstract

In order to design and manufacture robust electronic packages, it is important to understand the response of second and first housing levels to the climate conditions to which they will be subjected. Electrical and electronic devices are protected from outside environment by a second level housing, while semiconductor devices are encapsulated in a resinous thermoset material, or first level housing, called epoxy molding compound (EMC).
Moisture diffusion is one of the major reliability concerns, because many failure modes observed in the electronic devices are believed to arise from the diffusion of moisture during manufacturing, storage, or operation. Especially automotive electronic housings are exposed to environments in which the temperature and moisture content can vary drastically according to the geographical location and the location of the housings inside the car.
Moisture uptakes of electronic materials and moisture ingress into electronic housings have been studied by exposure to constant and cyclic conditions. Second level housings made of Polybutyleneterephthalate (PBT) and first level housings made of epoxy molding compound (EMC) were used. The new approach was to perform in-situ measurements of the temperature and the relative humidity inside the EMC, and generate a transfer function from outdoor to second and first level housing climates. The housings were completely tight, and the moisture ingress is only due to diffusion through the materials. The effect of the volume of the housing, the presence of Printed Circuit Board (PCB), and the self-heating of component have been studied. The results showed that the time constants for humidity to reach 63% of outdoor conditions are about 2 days and 7 days at 60°C, for the studied second and first level housings respectively, while the presence of PCB and the self-heating of component inside the device can slow down the ingress of moisture in the internal volume.

Key words: Humidity, temperature, diffusion, housing, epoxy mold compound, printed circuit board.

Introduction

In order to design and manufacture robust electronic packages, it is important to understand the response of the housing to the climate conditions to which they will be subjected during application. Electrical and electronic devices are protected from outside environment by an enclosure, the second level housing, while semiconductors are encapsulated in a resinous thermoset material, the first level housing, called epoxy molding compound (EMC).

Moisture diffusion is one of the major reliability concerns, because many failure modes observed in electronic devices are believed to arise from the diffusion of moisture during manufacturing, storage, or operation [1-2]. Especially automotive electronic housings are exposed to environments in which the temperature and moisture content can vary drastically according to the geographical location and the location of the housings inside the car.

The absorbed moisture also induces the degradation of the properties of polymers, e.g. plasticization and micromechanical damage [3-4], hydrolytic cleavage of polymeric chains, and therefore reduces the overall mechanical properties of the housings. The housing can act as a medium for the diffusion of humidity to interior of the device, which will reduce the reliability of electronic circuits inside. The internal ingress of humidity can lead to corrosion failure modes namely electrochemical migration and short circuit [5-12], or conductive anodic filament (CAF) formation between embedded copper conduction lines in glass epoxy laminate [13-15]. The internal moisture inside the second level housing will diffuse further into the first level housing and the local moisture concentration inside the EMC can induce electronic failures, due to interfacial delamination, reduction of the interfacial adhesion strength, material expansion, and mechanical failure [24], introducing intermittent malfunctions and permanent failures.

Prediction of the problems associated with moisture in electronic packaging requires a full understanding of the mechanism of moisture diffusion into the polymer packaging materials used in electronics and how it leads to humidity build-up inside the enclosure.

Although water absorption in PBT material [16-17], in the PCBA laminate [4; 18-20], and in EMC material [3; 21-23] have been investigated to a limited extent, no investigation is carried out on moisture penetration and build up inside the electronic enclosure under actual climate conditions with different levels of packaging.

In this paper, moisture diffusion into the housing materials is first investigated quantitatively by weight gain measurements using plastic packages as well as standard bulk materials. Ingress of moisture into the packaging has been investigated by exposing the electronic devices to various climate conditions, at constant conditions at 40 or 60˚C and 93% RH, and at two cycling profiles, representative of climate in Jakarta, Indonesia, and in the engine compartment of a car in south China. Further, the effect of humidity absorption by the printed circuit board including self-heating and role of condensation on the humidity buildup have been investigated. The moisture ingress into EMC has been studied by molding of the EMC material directly on a lead frame with RH and T sensors for in situ measurements of moisture absorption.

Materials and methods

Materials used for investigations

The materials selected for the water absorption studies are polybutylene terephthalate (casing material of the second level housings), epoxy mold compound (material of the first level housing), and PCBs (which are placed in the second level housings). Polybutylene terephthalate

(PBT) material is a semicrystalline polyester reinforced with 30% of glass fiber (30GF) with and without hydrolysis resistance (HR) property. Epoxy mold compound (EMC) is a composite material made up of an epoxy matrix (Biphenyl material) with silica fillers (~ 88 $_{wt.}$%), which also contains stress relief agents, flame retardants, and other additives. The PCBs are made of halogen and halogen-free FR4 laminates, which is glass fiber reinforced (fiberglass) epoxy resin with copper foils bonded on to the sides for etching out the circuits. Table 1: Details of material used for the investigations

The humidity build-up has been studied in two second level housings, namely Housing I and Housing II, which were made of PBT 30GF with and without HR respectively. For external electrical connections, the RH and T sensors were connected inside the housings to existing electrical pins avoiding any extra hole for connection.

For the in-situ measurement of humidity build-up in the first level housing, the RH and T sensors have been connected to a lead frame PLCC44 (Cu) (due to the size requirement of the sensors) using an Ag-filled epoxy with a curing process at 120 °C for 2 h. The lead frame has then been molded with the EMC material at 175 °C and 87 Bar pressure followed by a post-curing operation at 150 °C for 5 hours. Then the leads were stamped and trimmed followed by a Sn plating of the leads (Figure 1). The first level housing has the dimensions of 16.6 x 16.6 mm, a total thickness of 3.9 mm, and a thickness above the RH sensor of 1.1 mm.

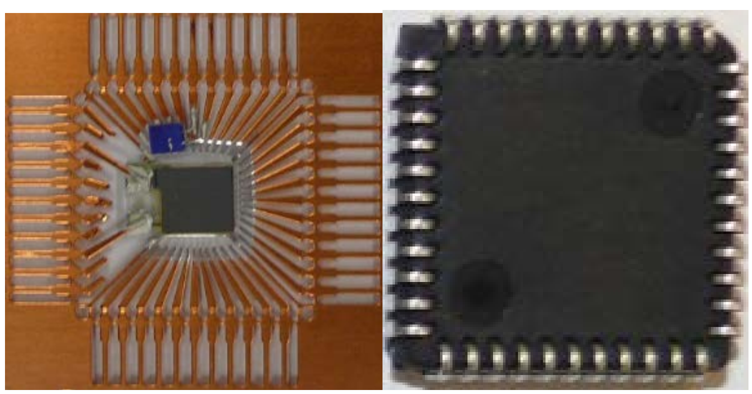

Figure 1: Pictures of a) Cu lead frame PLCC44 with connected T and RH sensors and b) after molding process of the ECM material.

Experiments on moisture uptake by polymer materials

The moisture uptake by the polymers is investigated to determine the diffusion, solubility, and permeability coefficients as well as the moisture saturation level of the materials. The two PBT materials with and without Hydrolysis Resistance (HR), EMC material, and PCBs were used for the investigation at conditions of 25 °C and full immersion in water, 40 °C and 93% RH, 60 °C and 93% RH, 85 °C and 85% RH.

All of the packages were dried (bake-out) prior to the test to remove any residual humidity. The exact bake-out condition should depend on the geometry and storage time of the packages. However, a standard baking condition for electronic packaging is 24 h at 120 °C. Therefore this baking condition is used in the present study in order to compare different packages. The initial weight was measured using a calibrated precision electronic balance (0.1 mg) followed by exposure in a climatic chamber. The samples were removed periodically from the climatic chamber to measure the increase in weight. Each time weight of the sample was measured after waiting to reach room temperature conditions. After weighing, they were placed again in the chamber for further sorption. Assuming an initial dry sample at the start of the sorption tests, the weight gain of the packages during the sorption experiment corresponds to the weight of moisture ingress into the package.

The percentage increase in moisture content (C(t)) at any time t, was calculated by using the following formula:

$$C\ (t) = \frac{m\ (t) - m_0}{m_0} \times 100 \qquad (1)$$

Where m_0 is the initial dry weight of the sample and $m(t)$ is the weight after an exposure time t. Considering the Fickian absorption, the diffusion coefficient of bulk materials D can be found from the slope of the initial linear part of the moisture uptake curve together with the sample weight at saturation state. The initial stage of moisture absorption ($m(t)/m_\infty < 0.5$) can be simplified as follows:

$$\frac{m(t)}{m_\infty} = 4\left(\frac{Dt}{\pi l^2}\right)^{1/2} \qquad (2)$$

Humidity exposure of housing and measurement of internal humidity build up

The housings are exposed to temperature and humidity conditions in a climatic chamber (model CTS, type C 40/200). Temperature sensors (PT1000) and humidity sensors (HC1000 – capacitive sensors) placed inside the housing as described before were used to record the interior temperature and humidity with a sweep time of 2 min (Datalogger GMH 3350, Greisinger electronic). Prior to the experiment, the RH sensors were calibrated at the two levels of humidity: 0% and 75% RH.

The constant climatic conditions used for the investigations were: 40 °C / 93% RH and 60 °C / 93% RH. Two cyclic conditions were studied: the first cycle corresponds to the 24 hour conditions at Jakarta, Indonesia (1st of July 2012) repeated for 115 days, while the second cycle corresponds to the actual data recorded inside the engine compartment of a car driving in southern China in the summer season including the simulation of parking and driving periods. The conditions are 30 °C / 85% RH during 22 h and 80 °C / 10% RH during 2 h respectively.

Results

Moisture uptake of the polymer packaging materials

Moisture uptake of PBT GF30 and EMC materials

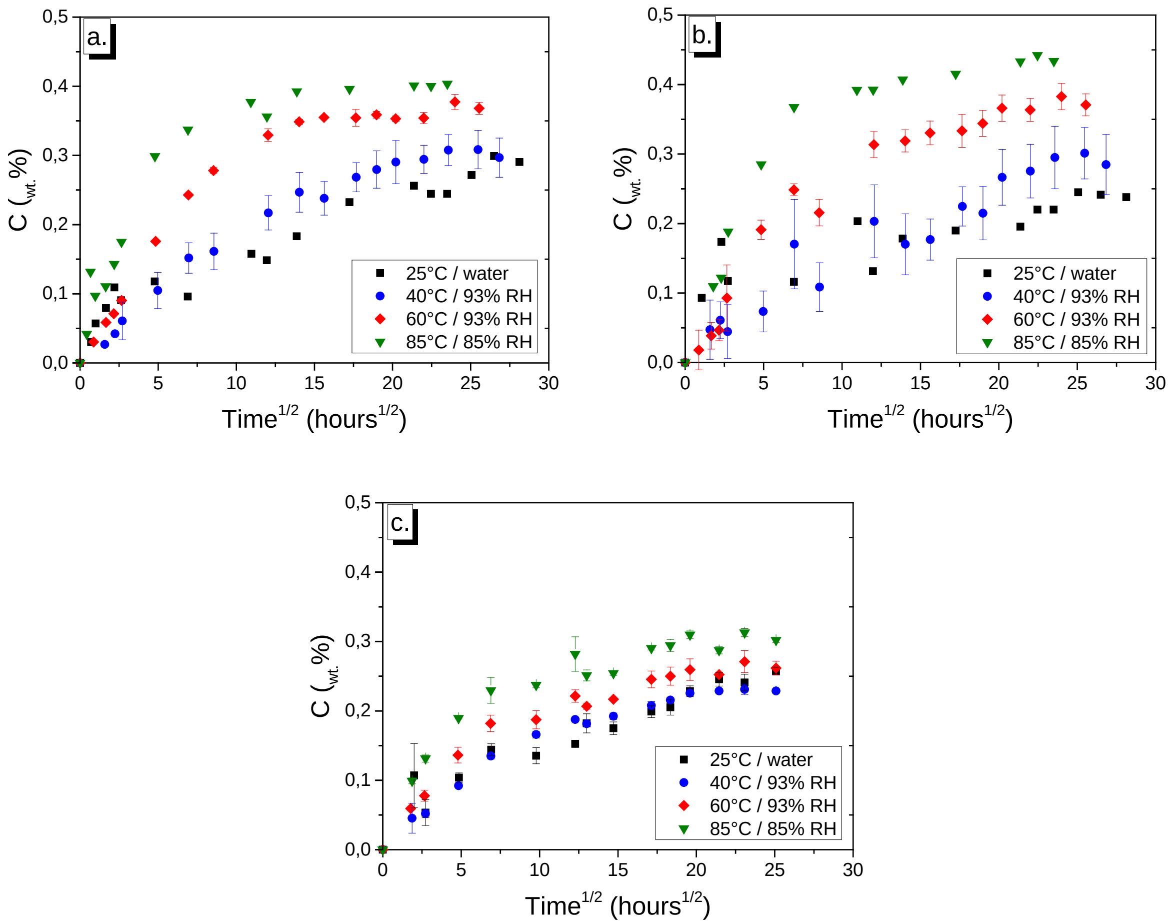

Figure 2: Moisture uptake of PBT: a) with HR and b) without HR, and c) EMC materials.

Figure 2 shows the plot of the experimental weight gain data showing moisture uptake as a function of the square root of time for PBT and EMC materials. The water uptake of the PBT samples with and without HR in Figures 2a and b shows an initial slope related to the relative rate of moisture absorption followed by a plateau region corresponding to the saturation level. The EMC material on the other hand showed a two-stage water absorption with the first part saturating after about 120 hours followed by a new increase of moisture absorption slope. The moisture uptake stabilized after about 700 hours of exposure. The saturated moisture content for the EMC material for all the four temperatures tested are about 0.21 $_{wt.}$%, 0.22 $_{wt.}$%, 0.24 $_{wt.}$%, and 0.29 $_{wt.}$%, while for PBT the values were about 0.25 $_{wt.}$%, 0.29 $_{wt.}$%, 0.36 $_{wt.}$%, and 0.40 $_{wt.}$%.The calculated Diffusion, Permeability, and Solubility coefficients increase with the increase of temperature. Overall, no distinct difference was observed between PBT with and without HR. The diffusion coefficients for the EMC material were significantly less than PBT at all temperatures (2.5, 3, 7, and 18 times less than the values for the PBT samples respectively at 25, 40, 60, and 85 ˚C).

Moisture uptake of PCBs

Figure 3 shows the moisture absorption profile for the PCB I and II at two different temperatures. Regardless of the temperature, the moisture absorption of the PCBs show an initial linear increase followed by a slow increase without reaching a maximum equilibrium moisture content after 45 days of testing under humid conditions. The weight of the PCBs continued to increase up to 0.35 and 0.44 $_{wt.}$% for the PCB I and up to 0.28 and 0.35 $_{wt.}$% for the PCB II at 40 °C and 60 °C respectively. This corresponds to the water absorption of the laminates and of the components of the PCBs.

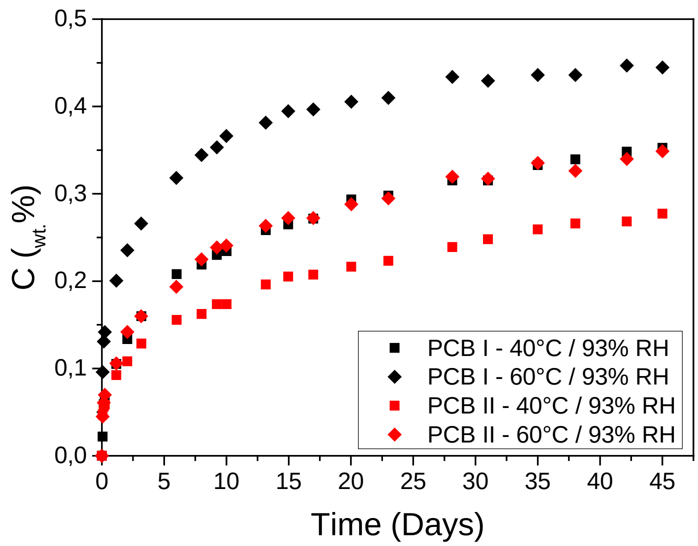

Figure 3: Moisture absorption by the PCB associated with the Housing I and II.

Exposure of the housings to constant conditions

Figures 4 shows the moisture ingress into the Housing I and Housing II (with and without PCB), and with EMC package placed inside the Housing II. The exposure conditions used were 40 °C and 60 °C with a relative humidity of 93%. The time constant T, i.e. the time to reach 0.63 of the outdoor RH, was respectively 7.7 and 1.6 days for the Housing I, and 10 and 2.9 days for the Housing II, at 40 ˚C and 60 ˚C. The humidity ingress in the Housing I was slower in the presence of the PCB I, with a reduction of 4% and 8% RH at the end of the test. The presence of the PCB II has slightly reduced the final RH inside the Housing II, however no significant difference was observed. The volume ratio of PCB / Housing is 14% and 6% for the Housing I and II respectively, while the PCB I found to absorb around 1.25 times more moisture than PCB II (Figure 3).

In order to determine the transfer function of the humidity through the second and first level housings, in situ measurements of the RH profile in the EMC material placed inside the Housing II has been performed. Figure 4 shows the RH profile at 60 ˚C and 93% RH, where a delay of the time constant about 11 days can be observed in comparison to the humidity build-up in the Housing II. The humidity had to diffuse through the second housing wall and then through the EMC material to be detected by the molded sensors.

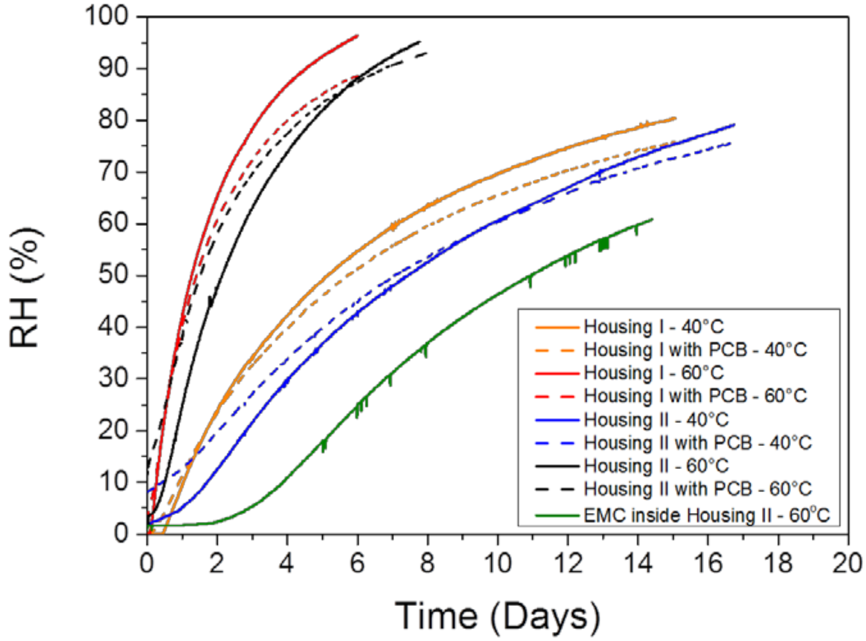

Figure 4: Moisture ingress into the Housing I and Housing II with and without additional components inside at different temperatures and 93% RH.

Exposure of housings to cyclic conditions

Simulated climate conditions of the day/night profile in Jakarta, Indonesia

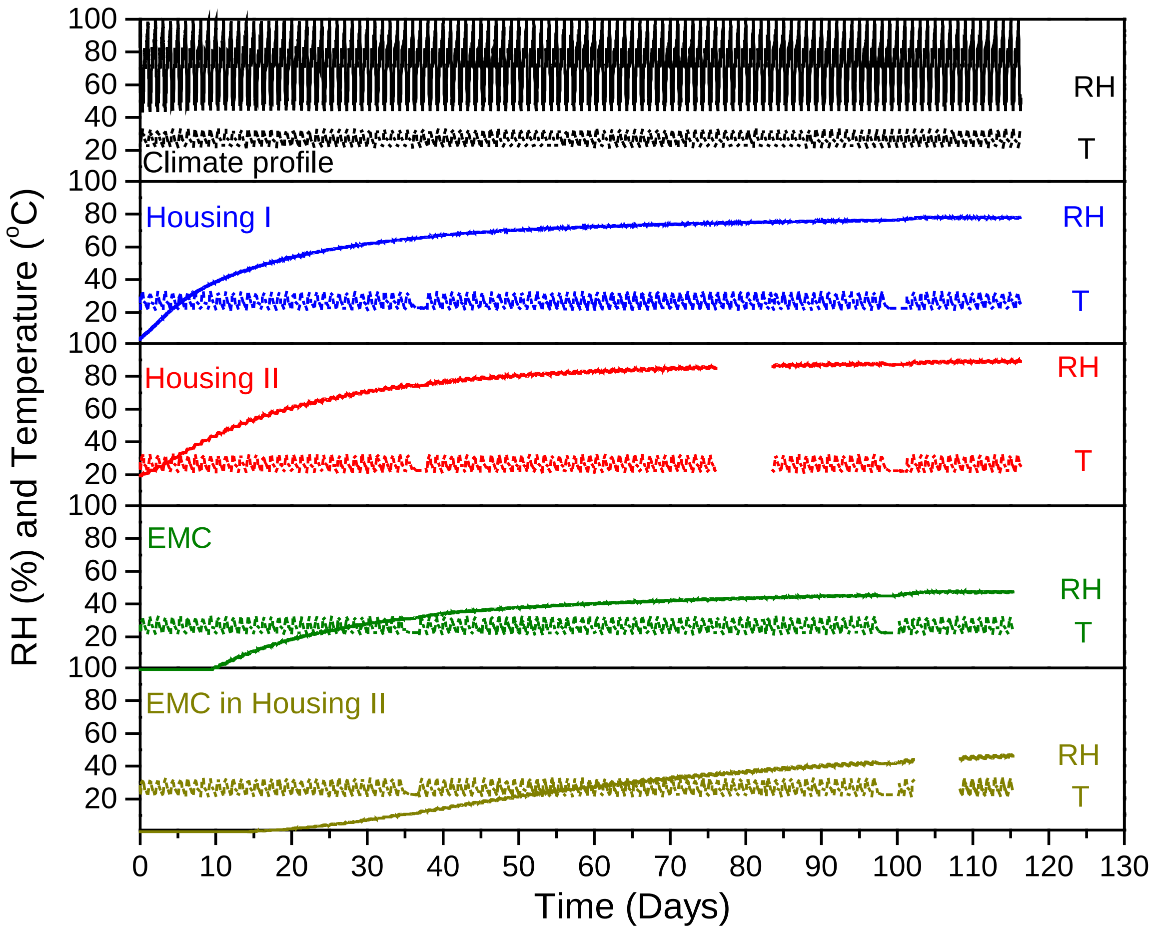

Figure 5: Climate profiles in Housing I, Housing II, EMC and EMC in Housing II exposed to the day/night profile in Jakarta, Indonesia.

Figure 5 shows the RH profiles in the Housing I and II with PCB exposed to the Jakarta profile. Results show that the internal RH level increased smoothly and did not follow the cyclic profile of the outdoor condition. Instead the internal humidity profile tends to reach a steady state value, around 78% RH and 89% RH for the Housing I and II. The in situ measurements of RH profiles in the EMC and for the EMC placed in the Housing II during exposure to the Jakarta profile showed an increase of the internal RH starting after 9.5 and 14.2 days respectively. A smooth increase of the internal RH was then observed, and reached a steady-state around 47% RH inside the EMC, but did not reach a plateau after 4 months of exposure to the Jakarta profile for the EMC placed inside the Housing II.

<u>Simulated climate conditions inside the engine compartment</u>

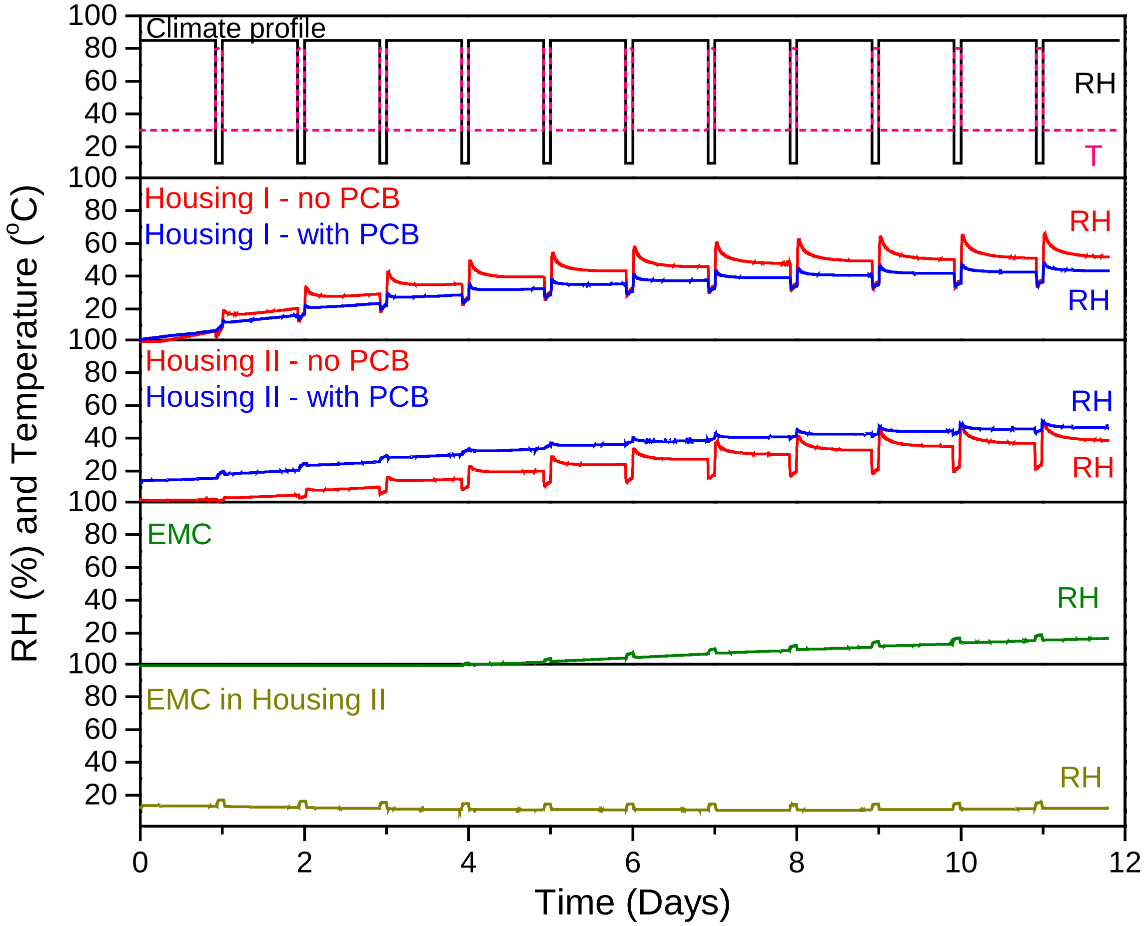

Figure 6: Climate profiles in Housing I, Housing II, EMC and EMC in Housing II exposed to the cyclic conditions: 30 °C / 85% RH / 22 h and 80 °C / 10% RH / 2 h.

Figure 6 shows the internal RH profiles from Housing I and II with and without PCB. In both cases without PCB, a similar profile can be observed. During the first step at 30 ˚C / 85% RH, the internal RH increased slowly. When the temperature is suddenly changed to 80 ˚C, a drop in the internal RH can be seen. However, when the outdoor RH level was 10%, the internal RH continued to increase despite its level was above the outdoor level of humidity. This excess of humidity can only come from the release of moisture from the wall. When the new step at 30 ˚C / 85% RH started, the internal RH increased suddenly at a higher level than at the previous step at 30 ˚C / 85% RH. This shows that more humidity has been accumulated in the internal volume during the step at high temperature (80 ˚C). Then the RH level decreased slowly until the next step, suggesting a re-absorption of moisture into the internal walls of the housings. The presence of PCB has a similar effect in both cases on the internal RH. The PCB acted as a buffer, and reduced the variation of humidity change in the internal volume during the step at high temperature.
The in situ measurements in the EMC material (Figure 6) did not show any increase of humidity until 4 days of exposure. Then, a slow smooth increase of RH is observed, with an increase of RH at each step at 80 ˚C suggesting that the EMC material released also moisture during the step at high temperature. The in situ RH measurement in the EMC inside the Housing II did not show any increase of humidity after 12 days of exposure. However, an increase of RH was also

observed during the step at 80 ˚C due to the release of initial moisture present at the beginning of the test in the EMC material.

Discussion

These investigations clearly show the effect of housing volume, presence of PCB, and self-heating on internal humidity build-up, and the transfer of humidity from outdoor to second and first level of protection, with PBT housing and EMC material. The second aim was to simulate cycling climatic conditions, such as day and night cycles in tropical area, and an internal report of temperature and humidity measurements inside an engine compartment of a car in China helped us to simulate the effect of driving and parking time on humidity build up inside the housings.

While the reliability of equipment is related to the RH [7; 25], the process of moisture diffusion through materials is related to the AH, i.e. the moisture concentration in air [26]. The studied housings being truly air-tight, permeation through the housing walls becomes the dominant transport mechanism. This will contribute to the approach to moisture equilibrium between the inside and the outside of the housing to reach similar AH levels.

While the rate of water absorption and the saturated water content (i.e. water content in equilibrium with its environment) of the different materials increased with temperature, the diffusion of the EMC material was lower than for the PBT materials. The HR property of the PBT samples did not have any effect on the diffusion. The PCB I can absorb more water than the PCB II, but both of them did not reach a saturated value after 45 days of exposure to humidity.

The low Diffusion coefficient of the EMC has induced a higher time constant (time to reach 63% of the outdoor condition) in the first level housing (EMC) compared to the second level housing (PBT). However, Shirangi et al. [1] showed that a higher amount of maximum moisture content in a package may be expected compared to its respective bulk molding compound. The difference can be attributed to the accommodation of water molecules at the interfaces between molding compound and the leadframe. However, in this study, the time constant for humidity build-up in the EMC mounted on the leadframe was around 2.8 times higher than the time constant of the housing II exposed to 60 °C.
The lower volume of the Housing I has led to a faster humidity build-up than in the Housing II, while the presence of the PCB I inside the Housing I has reduced the RH level of 4 and 8% at the end of the test, at 40 ˚C and 60 ˚C. The lower amount of absorbed water in the PCB II and the lower volume ratio between the PCB II and the Housing II have reduced the effect of delay in humidity build-up in the Housing II.
The self-heating of 5 and 10 ˚C inside the Housing II has lowered the internal RH level, while the internal AH has increased.

Actual outdoor humidity is not constant and that is where the housing protection can play a major role. The time constant of the housings is in the order of days or weeks depending on the temperature level when exposed to constant conditions. This time is long compared to the timescale for temperature and humidity changes of the weather during a typical day. The profile simulating the weather in Jakarta, Indonesia, during the day of 1st of July 2012 (Figure 5) showed that the maximum RH value corresponding to the steady-state was about 78 and 89% RH for the Housing I and II. An important function of moisture protection by housing materials is the attenuation of the ever changing ambient conditions, and in this tropical exposure simulation, the attenuation factor of the second level housing was about 10-20%, and this factor was enhanced up to 55% (after 4 months of exposure) in the first level housing placed inside the second level housing.

While the materials forming the wall between the humid outdoor conditions and the dry environment inside the housing will transmit moisture by permeation, the materials that have absorbed moisture from the humid environment will also release this moisture when exposed to a dry environment (release only to external climate) or to higher temperature (release to internal and external climate) [2]. This is what happened during the cyclic test II (Figure 6), where the moisture diffused and was absorbed by the walls during the step at 30 °C and 85% RH has been released during the step at 80 °C and 10% RH. During this step the absolute humidity has increased from 16 to 102 $g \cdot m^{-3}$ inside the Housing I, and from 12 to 63 $g \cdot m^{-3}$ inside the Housing II without PCB (last cycle). The drying period of this cycle (corresponding to the driving time of 2 h per day) has allowed the humidity absorbed by the wall material of the housing to be released, outside but also inside the housing volume, and this step was not long enough to dry out completely the housing. This shows that the heat induced during short periods of driving time is not enough to dry out the housings inside the car. This on the other hand could create higher level of humidity inside the housings due to release of moisture from the wall material. However, the absorption and release of moisture from the PCB have contributed to act as a buffer during the cyclic exposure to humidity, and have reduced the variation of the internal RH during the simulated driving period.

The released moisture of the EMC at 80 °C has actually also increased the internal RH level. In that case, there is no air gap between the material and the sensor, and any release of moisture from the EMC material will directly be in contact with the RH sensor surface. However, due to the low Diffusion coefficient of the EMC material, no increase of the RH has been observed after 12 days of exposure, when the EMC was placed inside the Housing II.

Conclusion

- While the moisture diffusion of PBT materials did not seem to be greatly influenced by the hydrolysis resistance property, the diffusion coefficient of PBT is around 6 times higher than the diffusion coefficient of EMC at 60 °C.

- The water uptake of PCB depends on the type of laminate, and heavy thermal mass components may be privileged places for condensation to occur, due to delay in temperature change.

- The moisture ingress into the second level housings was influenced by the temperature, the volume of the housing and the presence of the PCB.

- The exposure to simulated tropical profile (Jakarta, Indonesia) showed that the internal RH tends to reach a steady state, close to the mean value of the cyclic outdoor profile.

- The heat induced during short periods of driving time may not be enough to dry out the housings inside the car, and could actually create higher level of humidity inside the housings, due to release of moisture from the wall material.

- The in-situ measurement of moisture ingress inside EMC allowed to observe the transfer function of humidity from outdoor into the second level housing and into the first level housing. The low Diffusion coefficient of the EMC material has induced a high attenuation factor, up to 55% after 4 months of exposure to the Jakarta profile, when the first level housing was placed inside the second level housing.

Acknowledgements

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