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Multi-physics simulations for combined temperature/humidity loading of potted electronic assemblies

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ABSTRACT

The focus of this paper is on comparing alternate methods for conducting a multi-physics analysis of the stresses generated in potted electronics by temperature and humidity excursions. This study is motivated by the fact that electronics in consumer electronics are often embedded in a polymeric potting compound, in part to protect the electronics from shock or mishandling damage, and in part to increase the moisture barrier to protect the embedded electronics from moisture assisted failure mechanisms such as corrosion, dendritic growth, and conductive filament formation. However, moisture-induced swelling (expansion) and thermal expansion generates mechanical stresses in the embedded electronics and this can have deleterious effects on the reliability of the electronics. The example considered in this paper is that of aluminum electrolytic capacitors commonly used in driver electronics for solid-state lighting products. Mechanical stresses in the seals are known to affect the electrolyte leakage rates and hence affect the reliability of the capacitors. This paper focuses on multi-physics methods to analyze these stresses. The results show that the stress exerted by the potting compound is not a significant concern and accelerated stress test results are found to qualitatively support this finding.

1. Introduction

Reliability is one of the major concerns when a new product or component is designed and/or developed. Therefore, engineers have to evaluate the effect of environmental stresses, handling stresses and operational stresses on long-term degradation of performance. One of the approaches for increasing the reliability of electronics under lifecycle environmental conditions, including dynamic mechanical loads, mishandling or abuse, and moisture, is to embed the electronic assembly in an elastomeric potting compound. Silicone elastomer is a good potting compound because of its compliance and low moisture diffusivity. Unfortunately, the potting compound can potentially increase the risk of some other failure modes and even introduce new failure modes which need to be critically examined and evaluated.

An important example of potted electronics in contemporary products is the driver electronics for solid state lighting (SSL) products, such as the LED light bulb shown in Fig. 1. The potting is used to protect the electronics from the life cycle stresses listed in the previous paragraph. Many researchers have indicated that conventional commercial LED components in SSL systems have been found to survive much longer than the driver electronics [11,12]. Therefore, our focus in this study is on stresses in the potted driver electronics.

A key step for assessing the various failure modes is to first identify all the stress conditions generated by the operating and environmental loading conditions which the unit will experience throughout its lifecycle. The focus in this study is on the environmental stresses, not on the operational stresses generated during power cycling. A SSL bulb may experience indoor environment or outdoor environment, depending on the application. Therefore, a SSL bulb and its driver electronics are expected to experience temperature and humidity excursions, causing thermo-hygro-mechanical deformations in the potting compound and hence in the embedded electronics. The goal of this paper is to present multi-physics modeling approaches that are needed to assess the severity of such stresses. Other applications such as handheld lighting devices or automotive lighting devices may also expose the electronics to dynamic mechanical loading but these are beyond the scope of the present paper.

In the typical example presented in Fig. 1, the driver electronics consist of a printed wiring assembly (PWA) potted with silicone rubber inside a plastic PVC cylindrical housing. The component of

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most interest in the PWA is a large aluminum electrolytic capacitor. Historical experience indicates that electrolytic capacitors are often the weakest component in the driver electronics with the lowest rated life expectancy compared to the other components in the system [12]. A typical aluminum electrolytic capacitor consists of a roll of electrode sheets soaked in a liquid electrolyte and sealed with a butyl rubber cap inside a long cylindrical aluminum can. The leads are attached to the electrodes and egress the package through holes in the butyl rubber.

An electrolytic capacitor is composed of two parallel sheets of aluminum which form the anode (positive) and cathode (negative), separated by a paper which is soaked in electrolyte. Between the interface of the electrolyte paper and the anode foil a thin oxidation layer of the dielectric (Al_2O_3) layer forms [10]. The electrolyte inside the electrolytic capacitor is essential for holding the charge of the capacitor. One of the primary degradation modes for such capacitors is the slow leakage of the volatiles in the electrolyte through the butyl rubber [9] and through the interfaces where the rubber cap meets the leads and the aluminum can. As the electrolyte evaporates and leaks out of the capacitor, the capacitor's ability to hold charge decreases until the electrolyte paper dries up and the capacitor behaves as an open circuit in the driver electronics.

The potting material in such electronic systems can be expected to potentially affect four different degradation modes. (1) Thermo-hygro-mechanical expansion and contraction of the potting compound present a potential risk for electrolyte leakage, because of the cyclic volumetric changes it can generate in the capacitor can [2]. (2) The resulting mechanical hydrostatic stresses acting on the butyl rubber seal of the capacitor can affect the diffusion of the electrolyte through the seal and permeation through associated interfaces. (3) The surface stresses between the PWB and the silicone elastomer (potting compound) can lead to delamination which could then become pockets for moisture accumulation. The accumulation of moisture in the delaminated regions presents potential risk of corrosion of metallization on the surface of the PWB. (4) The potting compound can affect the heat transfer rate from components that are dissipating heat. This can raise the temperature of the driver electronics and thereby affect its reliability.

Among the four failure modes discussed, the first three are multi-physics phenomena and are of interest in this study. In particular, we focus on failure modes (1) and (2). As discussed earlier, one of the dominant degradation modes for electrolytic capacitors is the progressive loss of capacitance due to leakage of electrolyte from the capacitor. The electrolyte leakage rate is driven by the diffusivity of the butyl rubber as well as the compressive stresses at the interface between the butyl rubber seal and the leads. The leakage rate is also dependent on the hydrostatic pressure within the aluminum can. This pressure is generated not only by the volatiles and the hydrogen gas generated within the capacitor, but also by any external hydrostatic stresses that tend to squeeze the can, such as those due to volumetric changes in the surrounding potting compound. Therefore, the focus of this paper is on the stress fields that can accelerate this leakage process. This paper presents alternate methods to analyze the external stresses exerted on the capacitor due to the thermo-hygro-mechanical deformations in the potting compound. Multi-physics finite element analysis (FEA) is conducted to identify the resulting hydrostatic stresses and radial stresses in the potting compound as well as in the butyl rubber seal.

The temperature and humidity excursions used in the FEA for this study are motivated by an accelerated life cycle test, reported later in this paper, which has been conducted on the potted driver electronics of a LED light bulb assembly, similar to the one shown in Fig. 1. This profile consists of a 24 h cycle between two extreme conditions of 30 °C–30%RH and 75 °C–85%RH.

2. FEA approach

To determine the thermo-hygro-mechanical stress fields in the driver electronics, we need to understand the temperature distribution, moisture distribution and their coupled effects on the mechanical deformations. Multi-physics FEA is a useful way to estimate these coupled changes in the thermal field, moisture field and mechanical field [13–15].

Any such analysis must also account for any initial residual fields caused by the prior manufacturing and handling history of the product. In this example, we will assume that the initial temperature field is uniform room temperature and that the product has been baked and stored properly to ensure an initially dry condition. The initial mechanical field must account for the curing-induced residual stress field. Thus it is important to first model the curing-induced chemical shrinkage, which is the volumetric reduction during the curing stage of the potting compound, since this step may generate a significant contribution to the overall stress field.

After the initial residual fields are estimated, the next step is to estimate how both temperature and humidity undergo simultaneous changes in the physical problem. The temperature field is assumed to have a negligible dependence on the moisture field, but the moisture concentration is known to be strongly dependent on the temperature field because of the thermal dependence of the moisture diffusivity constants. Therefore, in the modeling approach, the thermal field is determined first, followed by the humidity field.

Many commercial FEA codes combine thermal transport analysis with thermo-mechanical analysis but do not provide a similar capability to combine mass diffusion analysis with hygro-mechanical analysis without the use of special user subroutines. Thus it is not possible to model the mechanical effect of simultaneous changes in the thermal and moisture fields in polymers, without appropriate user subroutines. One alternate solution therefore is to approximate the problem with a sequential analysis, where the mechanical effects of changes in the thermal field and moisture field are modeled sequentially. In this sequential approach, the moisture transport is modeled with an equivalent thermal transport analog, so that the resulting hygro-mechanical changes can be captured through a corresponding thermo-mechanical analog. Details of this transformation are discussed in Appendix A. Therefore, the two alternate approaches presented are the sequential approach and the simultaneous approach.

As discussed earlier, the initial step in both approaches is to estimate the residual mechanical stresses due to chemical shrinkage during the curing process. This is done with a pseudo thermo-mechanical analysis, as described in Appendix B.

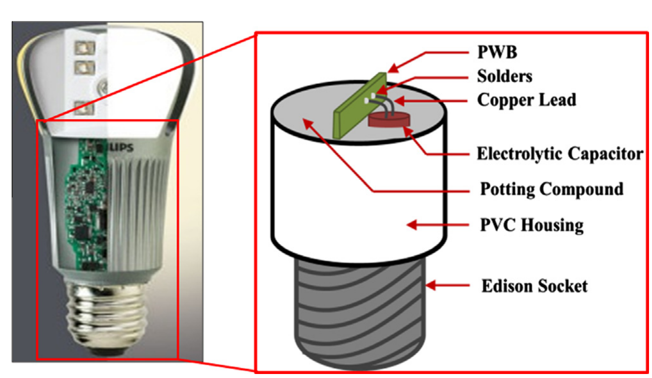

Fig. 1. The schematic on the right is depicting the potted driver electronics for LED light bulb similar to the image on the left [16].