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Eliminating infant mortality in metallized film capacitors by defect detection

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ABSTRACT

A PoF approach to mitigating infant mortality is proposed which includes (1) conducting reliability capability and product maturity analyses; (2) identifying defects through non-destructive analysis, if possible; and (3) developing electrical tests to screen out early failures. The non-destructive analysis approach was outlined using die attach in a power module as a test bed, while the electrical testing approach was outlined using film capacitors. More data is being gathered to validate that the electrical test provides an early differentiation of change in capacitance over time between good and defective capacitors.

1. Background

1.1. Review on nature of infant mortality

Traditional reliability analysis utilizes a hazard rate curve, known as the bathtub curve, which is shown in Fig. 1. It is a graphical representation of the lifetime of a population of products. The curve is divided into the following three segments. The first are failures that occur early in the life of the product, called "infant mortality," which are characterized by a decreasing failure rate. The second are failures that occur during the normal life of the product, characterized by a constant failure rate. The third are failures that occur near the natural end of the product life, called "wear-out failures", characterized by an increasing failure rate.

From the physics-of-failure perspective, all failures, regardless of the failure rate trend or time at which the failure occurs in the product life, are caused either by a stress that exceeds the strength of the product or by a fundamental chemical, electrical, thermal or mechanical degradation process. Wear-out failures occur in products that are manufactured to design specifications and happen when the materials of construction have accumulated sufficient damage to exceed their resistance to failure (e.g. fatigue life). Failures that occur during normal life are often due to unexpected overstress events that exceed the strength of the material (e.g. lightning strike, power surge). Early failures or infant mortality failures typically occur in product containing manufacturing flaws that reduce the robustness of the product against overstress or accelerate the accumulation of damage leading to early wear-out. As infant mortality failures are primarily due to defects caused by poorly controlled manufacturing processes, they are usually not a concern with mature products from high quality manufacturers.

While high durability and a long application life are desirable in all cases, there are a number of applications in which the elimination of infant mortality failures is of paramount importance. These include power systems where maintenance and repair are difficult or impossible. Examples are variable frequency AC converters in offshore wind turbines, DC power supplies for satellites, and electronics for deep sea underwater oil and gas exploration. In such applications, inaccessibility makes high reliability essential, especially in the early life of the product.

Since the bathtub curve represents the failure rate of a population of product over time, it is possible to eliminate infant mortality by identifying the potential early failing units using screening methods. Then, the remaining population will fall in the "defect-free" normal life period with a comparatively low constant failure rate. A typical approach to minimizing infant mortality failures is to conduct a burn-in test. This consists of running all the devices manufactured for a set period of time necessary to ensure that all of the infant mortality failures have occurred, and thus corresponding to the infant mortality segment of the bathtub curve. Product that is subject to infant mortality will fail in the test, while product the passes the test is then released to the field. In this study, we will focus on a newer approach, which is to either find the defects through non-destructive analytical techniques, or through the use of a defect-specific robustness test that is correlated to the lifetime.

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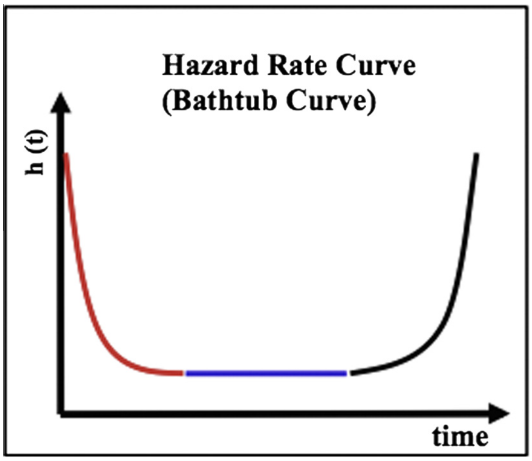

Fig. 1. Hazard rate curve.

1.2. Disadvantages of burn-in testing

Burn-in testing has serious disadvantages. It is relatively expensive and delays market release because the entire lot of products must go through the test in order to screen out the defective units. In addition, the test is not useful in identifying failures in mature products where (1) defects tend to be carefully controlled or eliminated already; (2) statistical process control (SPC) techniques are employed to keep quality in control and keep parts within tolerance; and (3) infant mortality failures are not typically observed. The last and most undesirable disadvantage is that the test consumes a significant fraction of the useful lives of the entire population of the product under test. In many cases, damage from the burn-in test outweighs the benefits of eliminating the early failures, especially for mature products from quality manufacturers.

2. PoF alternative to burn-in

To address the issue of mature product, reliability capability and device maturity analyses can be conducted in advance of burn-in or screening to confirm the need for infant mortality mitigation in the components of interest. These analysis are detailed in IEEE Std 1624-2008 – "IEEE Standard for Organizational Reliability Capability," published in February 2009. IEEE 1624 is a standard for assessing, in a consistent manner, organizational reliability capability, which is a measure of the practices within an organization that contribute to the reliability of the final product, and the effectiveness of these practices in meeting the reliability requirements of customers. If the product is not mature or the manufacturer does not meet the standard, it is necessary then to pursue infant mortality mitigation methods.

To address the other limitations of burn-in, the PoF approach to the analysis of product failures is conducted on those devices that require infant mortality mitigation. Here the defects that could potentially accelerate particular failure mechanisms leading to early failure are identified, either through non-destructive analytical techniques or by tailored robustness testing, and product containing those defects removed without the need for burn-in testing.

2.1. Common non-destructive techniques (NDTs)

With the help of non-destructive analytical techniques, defects of interest can be observed and quantified. Then, the effect of these defects on reliability can be evaluated by experiment or finite element analysis (FEA) as a function of defect size, shape, and distribution. As a result, defective units can be eliminated from the population by the PoF method without consuming any life in the good units. Non-destructive techniques for detecting defects fall into the following three main categories: physical, electrical and thermal:

(1) Physical approaches visualize a defect directly. Examples of this include detection and quantification of a void or crack in die attach either by X-ray tomography or scanning acoustic microscopy (C-SAM).
(2) Electrical approaches detect defects by their effect on the output signals of the device. These include detection of excessive intermetallic formation in a wirebond by RF impedance, or of a missing solder joint by continuity (open circuit) at a pin
(3) Thermal approaches detect defects by their effect on the ability of the device to shed heat and thus on its temperature profile. Examples include detection of cracks in die attaches or substrates by an increase in device junction temperature.

2.2. Example: eliminate infant mortality in die attach

Work has been done to eliminate infant mortality in power modules by using the PoF approach to identify voids and cracks in the die attach. Voids and cracks in die attach are found to reduce the fatigue life of attach during power cycling. The procedures to eliminate potential early failing units are as follows:

(1) Die attach cracks are identified and quantified by C-SAM (see Fig. 2). Voids are identified and quantified by X-ray tomography.
(2) The effect of a crack or void of a given size and shape on the thermal resistance of the die attach layer is determined using thermal analysis.
(3) The effect of a pre-existing crack or void on on-state device junction temperature is determined by electrothermal modeling. Electrothermal modeling relates the junction temperature of a power device to the power loss from the device in the on-state for a given package containing a passive stack of known thermal resistance. The presence of the crack or void in the die attach increases the thermal resistance of the stack relative to that of the defect-free stack, thus raising the on-state junction temperature.
(4) The increased junction temperature creates an increase in the temperature cycle range for an application with a given power cycle, thus creating more thermo-mechanical damage in each cycle, decreasing the life. A recursive degradation

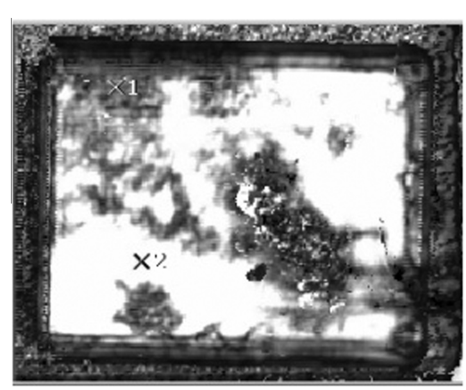

Fig. 2. C-SAM image of a cracked die attach.