Reliability Engineering and System Safety 154 (2016) 152–159

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Lumen degradation modeling of white-light LEDs in step stress accelerated degradation test

Jianlin Huang [a,*], Dušan S Golubović [b], Sau Koh [c,1], Daoguo Yang [d], Xiupeng Li [e], Xuejun Fan [f,2], G.Q. Zhang [g,3]

[a] *Beijing Research Center, Delft University of Technology, Beijing 100083, China*
[b] *Lumileds Commercial (Shanghai) Co., Ltd, Shanghai 200233, China*
[c] *Beijing Research Center, Delft University of Technology, Beijing, 100083, China*
[d] *Guilin University of Electronic Technology, Guangxi 541004, China*
[e] *Philips Lighting, Shanghai 200233, China*
[f] *State Key Laboratory of Solid State Lighting, Beijing 100083, PR China*
[g] *Delft University of Technology, CT 2628, Delft, the Netherlands*

ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form
13 April 2016
Accepted 5 June 2016
Available online 7 June 2016

Keywords:
Accelerated test
Brownian motion
Degradation test
Light-emitting diodes
Step stress
Wiener process

ABSTRACT

In this paper, lumen degradation is described by using a modified Brownian motion process for mid-power white-light LED packages, which were aged under step stress accelerated degradation test (SSADT). First, a SSADT model has been established based on the theory of equivalent accumulative damage. Then, a method was proposed to improve the accuracy of the parameter estimation by carefully modifying the estimator, which was proposed in the previous research. Experimental data show that parameters estimated by using SSADT model are very close to those estimated by using constant stress accelerated degradation test (CSADT) model, indicating the feasibility of the SSADT model. The experiment also indicates that SSADT can be used as an alternative to CSADT, as it enables comparable estimation accuracy, while using less testing time, a smaller sample size and less test capacity.

1. Introduction

MID-POWER white-light LEDs (MP-LEDs) have been widely considered as the new generation of luminaires due to their advantages of higher efficiency, longer lifetime, and more environment protections as compared to currently widely used lighting solutions (incandescence, fluorescence). Recently, due to fast evolution of the technologies, the lifetime of LED packages has been claimed to be as high as 50,000 h. For such kind of products, failed units would be seldom observed during life tests, even though they are subjected to accelerated conditions. Therefore, it is unreasonable to collect failure data for LED reliability analysis by performing accelerated life test (ALT) in which samples are generally recorded as time to failure.

Though catastrophic failures are seldom observed, LED packages showed gradual degradation during ageing tests. The degradation includes lumen decay, color shift [1,2], and so forth. For these kinds of devices, it is possible to obtain degradation measurements over time, and these measurements may contain useful information about product reliability. By using these degradation data, the lifetime of LED packages can be estimated, according to the IES standards [3,4]. The test method and related data analysis techniques in these standards, are typically called accelerated degradation test (ADT), which have been studied for many years [5–7]. Researchers have also developed several statistic models for this kind of accelerated tests. These models are categorized into either general path model [8–11], or stochastic process model [12–16]. A review of the degradation modeling can been found in [17].

In general, constant stress accelerated degradation test (CSADT) and step stress accelerated degradation test (SSADT) are two of the most popular ADTs in industry applications. Compared to CSADT, SSADT enables comparable lifetime prediction accuracy while using smaller sample size and less test resources [18–20]. Therefore, the

---

[*] Corresponding author.
E-mail addresses: J.Huang-37@tudelft.nl (J. Huang), dusan.golubovic@lumileds.com (D. Golubović), saukoh@sklssl.org (S. Koh), d.g.yang@guet.edu.cn (D. Yang), Xiupeng.Li@philips.com (X. Li), xuejun.fan@lamar.edu (X. Fan), G.Q.Zhang@tudelft.nl (G.Q. Zhang).

[1] Now with Huawei Technologies Co., Ltd., Shenzhen, China

[2] With Lamar University, Beaumont, TX, 77710, USA

[3] Working for Institute of Semiconductors, Chinese Academy of Sciences, Beijing, 100083, PR China

http://dx.doi.org/10.1016/j.ress.2016.06.002
0951-8320/

SSADT has been widely applied in reliability tests for LEDs [21,22], transistors [23], and missile tanks [24]. Based on Nelson's equivalent accumulative damage theory, Tseng [18] and Weiqiang [25], respectively, presented a segmented nonlinear accelerated degradation model (SNADM), which tackles the problem that the degradation rate of the products varies with time during SSADT. However, these models are regression-based and, thus, they cannot capture the dynamics or random variations of the degradation process. In order to solve this problem, Doksum et al. [26], Liao et al. [27], and Tsai et al. [28] proposed a stochastic-based SSADT model using Brownian motion and Gamma process. The stationary and independent incremental property of the stochastic processes renders simplicity of the modeling of SSADT.

The drawback of these stochastic models is that, they are only available for linear degradation behaviors, thus limiting the applications in a more broad class of degradation processes. Over the past years, researchers were making efforts to develop more flexible models for directly describing the nonlinear degradation through a stochastic process [29–33]. More recent works can be referred to the publications of Si et al. [34,35], Zhao-Qiang et al. [36], Wang et al. [37,38], Wang et al. [39], Zeyi et al. [40], Chiang et al. [41]. In these papers, researchers have modeled nonlinear degradation by using time-scaling techniques [37–39,41], nonlinear drift coefficient [29–34], or an adaptive parameter which can be updated dynamically [35,36,40]. While these models have only been developed for the degradation process in CSADT, there are few studies for the SSADT modeling, which use stochastic models to describe nonlinear degradation processes [27,42].

In this paper, we presented a methodology for the SSADT modeling based on a modified Brownian motion. Firstly, the theory and characteristics of modified Brownian motion are introduced. Secondly, the SSADT model has been established by using the modified Brownian motion theory. Thirdly, a likelihood function was presented for the parameter estimation. Finally, a set of experiments, including CSADT and SSADT, were conducted on one type of mid-power white-light LED packages. After the experiments, parameter estimation was performed on data obtained from both SSADT and CSADT in order to verify the feasibility of our SSADT model.

2. Modeling of step stress accelerated degradation test

2.1. Theory of Brownian motion process

The modified Brownian motion $\{X(t),\ t \ge 0\}$ is defined as [37,43]:

$$X(t) = X(0) + \int_0^t \mu(t;\ \theta)dt + \sigma B(t), \tag{1}$$

where $\mu(t)$ is the drift rate, σ is the diffusion coefficient, and $B(t)$ is the standard Brownian motion. Generally, the basic properties of Brownian motion could be characterized as follows:

(P1) The increment $\Delta X(t) = X(t + \Delta t) - X(t)$ is independent of $X(t)$, which means that if $0 \le s_1 < t_1 < s_2 < t_2$, then $X(t_1) - X(s_1)$ and $X(t_2) - X(s_2)$ are independent random variables, and the similar condition holds for n increments;

(P2) $\Delta X(t) \sim N\left(\int_s^{s+t} \mu(\tau;\ \theta)d\tau,\ \sigma^2 t\right)$,

where $N\left(\int_s^{s+t} \mu(\tau;\ \theta)d\tau,\ \sigma^2 t\right)$ denotes the normal distribution with expected value $\int_s^{s+t} \mu(\tau;\ \theta)d\tau$, and variance $\sigma^2 t$.

(P3) According to (P2), if $s = 0, X(t) \sim N\left(\int_0^t \mu(t;\ \theta)dt,\ \sigma^2 t\right)$.

Assume under a certain stress level S_k, the LED's lumen degradation $X_k(t)$, can be described by Brownian motion. According to Eq. (1), we have

$$X_k(t) = \int_0^t \mu_k(t;\theta)dt + \sigma_k B(t). \tag{2}$$

Given a threshold w, the LED is deemed to fail once the observed lumen degradation $X_k(t)$ crosses the specified threshold. From the first hitting time (FHT) concept, the lifetime T can be defined as

$$T = \inf\{t\colon X_k(t) \ge w | X_k(0) < w\}. \tag{3}$$

By transforming the problem from calculating the FHT distribution of the nonlinear diffusion process crossing a constant threshold into a standard Brownian motion process crossing a time-dependent boundary, the probability distribution (PDF) of $X_k(t)$ crossing a constant boundary w has been derived by Si et al. [34]. Furthermore, with the assumption that the probability of such a degradation process crosses the threshold level before time t is negligible, the explicit form of an approximation to the PDF of the FHT distribution was given as follows [34]:

$$p_{X_k(t)}(w,t) \cong \frac{1}{\sqrt{2\pi t}}\left(\frac{S_B(t)}{t} + \frac{1}{\sigma_k}\mu_k(t;\theta)\right) \cdot \exp\left[-\frac{S_B^2(t)}{2t}\right], \tag{4}$$

where $S_B(t) = \frac{1}{\sigma_k}\left(w - \int_0^t \mu_k(\tau;\ \theta)d\tau\right)$.

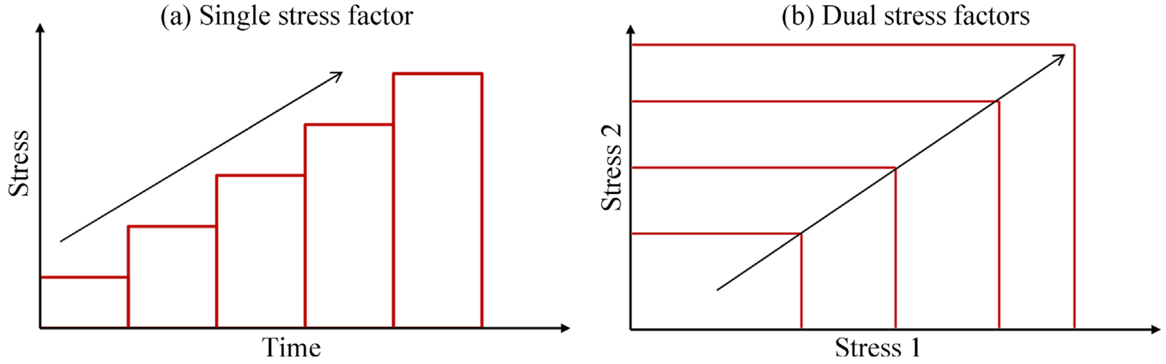

Fig. 1. Step stress pattern with different stress factors.