



Determining the effect of burn-in process on reliability of X7R multilayer ceramic capacitors

Pedram Yousefian^{1,*}  and Clive A. Randall¹

¹ Materials Research Institute, Department of Materials Science and Engineering, Center for Dielectrics and Piezoelectrics, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

Base metal electrode (BME) multilayer ceramic capacitors (MLCCs) continue to advance with higher volumetric capacitance, higher voltage, and higher-temperature operational ranges with greater numbers of capacitors being manufactured and integrated into the electronic infrastructure of society. Many of these applications range from aerospace, transport, computation, medical, satellite, military, and the internet of things means the interdependence of these devices require higher reliability at a collective and individual component level. Thus, determining the lifetime reliability of MLCCs is critical to provide more reliable components, and no weak links to the electrified infrastructure. For some of the more costly systems that support military and satellite systems, the reliability testing is very extensive. The burn-in test is a screening procedure used to remove components with higher probability of infant mortality failures. In this process, components are exposed to high temperatures and voltages relative to their design. The thermal stimulated depolarization current results revealed that burn-in test caused the intragranular and transgranular migration of oxygen vacancies, which will not be relaxed after the burn-in test. Time to failure data obtained through in situ highly accelerated lifetime tests demonstrated that not only burn-in tests were ineffective at detecting infant mortality failures, but they also had a negative impact on reliability of BME MLCCs by creating a weak population. The electromigration of oxygen vacancies during burn-in tests shorten the lifetime of MLCC population by reducing the protection effects of double Schottky barriers at the grain boundaries and electrode interfaces.

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Address correspondence to E-mail: pyousefian@psu.edu

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Introduction

MLCCs are among the most common passive components in consumer, automotive, medical, and military electronics [1, 2]. According to business wire, the annual global MLCCs production volume reached about 4.5 trillion devices in a \$10.28 billion value market in 2020 and is expected to grow at a compound annual growth rate of 7 to 9 percent until 2026 [3]. To overcome the limitations of precious metal electrode (PME) MLCCs in downsizing, BME MLCCs were developed to keep up with miniaturization and increase the volumetric capacitance of MLCCs by reducing dielectric thickness. Regardless of MLCC technology, MLCCs can experience reliability issues and their dielectric materials are always susceptible to dielectric breakdown or time-dependent degradation processes when exposed to high fields in their operations [4–7]. Significant advances in understanding of the materials, processing, properties, and reliability of BME MLCCs over the last few decades have led to their widespread use in long-term sensitive reliability electronics, elevating the importance of BME MLCCs' reliability analysis.

The hazard rate $\lambda(t)$, or instantaneous failure rate, of products is commonly used for statistical reliability analysis whose shape is determined by the timing of failures incident over time. Because of uncertainty, it is impossible to assign a “fixed shape” to the hazard rate curve; however, the bathtub curve is the most common shape of hazard rate curves assumed for electronic components and products, as shown schematically in Fig. 1. In general, the bathtub curve consists of three sections: the first section is related to failures that occur early in the life of product and is characterized by a decreasing failure rate ($\beta < 1$),

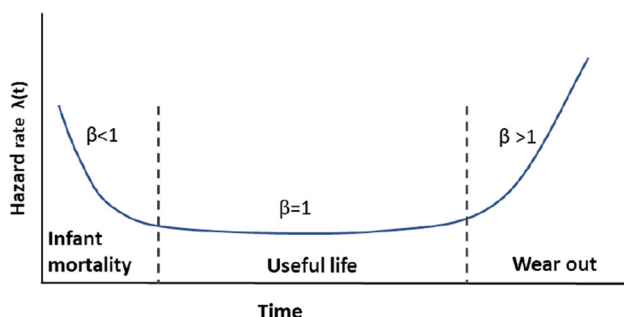


Figure 1 Schematic of hazard rate curve where β is the slope of the hazard rate curve.

called “infant mortality.” Second section is related to random failures that occur during the expected life of product and is characterized by a constant failure rate ($\beta = 1$), and the third section is associated with failures that occur near the natural end of the product life and is characterized by an increasing failure rate ($\beta > 1$), called “wear-out failures” [8]. Recently, Goankar et al. [9] stated that the bathtub curve is frequently misused to express electronic components hazard rate curves, and it is rarely used in its entirety. Earlier, Wong and Lindstrom [10] mentioned that the hazard rate curve resembles more of a roller-coaster shape than the bathtub curve because of latent failures and multiple failure mechanisms involved in electronic components.

Although the overall engineering goal in consumer products is to produce durable components and a prolonged application life within economic constraints, it is far more important in aerospace and military applications to avoid infant mortality failures without sacrificing long-term reliability. As a result, strict and robust performance specifications, such as MIL-PRF-32535A, have been used to ensure that products meet specific requirements [11]. According to this standard, the entire lot of produced capacitors must be tested at two or four times the rated voltage at 125 °C for 168 and 21 h, respectively, to eliminate components with a higher likelihood of infant mortality failures. This process is commonly referred to as the burn-in test.

Understanding the failure rates during burn-in testing allows for strategic component screening and learning the population survival rate, all with a constant failure rate. The burn-in process is costly and time-consuming, and it may shorten the life of the MLCCs. The burn-in process has implication on accumulation of subcritical oxygen vacancies, which may not relax after the screening, as schematically shown in Fig. 2. If this is the case, the time-dependent breakdown is compromised because electromigration of oxygen vacancies is the most acknowledged degradation mechanism of MLCCs under the dc bias [5], which leads to moderate the effect of essential barriers, like grain boundaries and electrode interfaces, in MLCCs degradation [12]. Thus, the objective of this study is to investigate the effect of burn-in process on reliability of BME MLCCs. Details of the TSDC, impedance and microstructural evolution of degraded BME MLCCs have been reported earlier

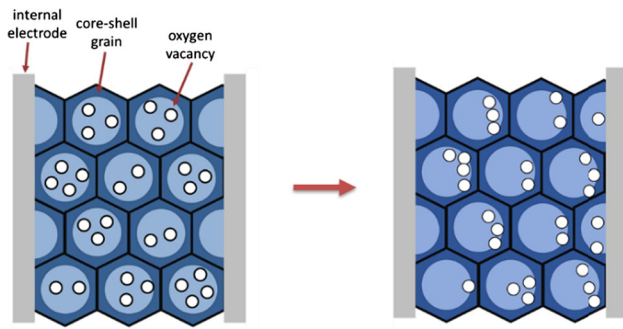


Figure 2 Schematic of the electromigration of oxygen vacancies during burn-in process.

and used to address the interpretation of the new data noted in this investigation [6, 7, 13, 14].

Experimental procedure

Commercial BME X7R MLCCs (1206 case size, 1 μF , and voltage rating (V_r) of 50 V) were used for this study to investigate the dynamics of oxygen vacancies and the associated space charge distribution during burn-in test. As shown in Fig. 3, these BME X7R MLCCs have a dielectric thickness of 60 μm with Ni electrodes. X7R MLCCs are the most common class II capacitors known as stable capacitors [15, 16]. The electronic industry alliance (EIA) specification for X7R MLCCs is a temperature variation of capacitance ($\Delta C/C$) of less than 15% between -55°C and 125°C [17].

Burn-in tests were carried out at 125°C with DC fields of $2 \times V_r$ for 168 h and $4 \times V_r$ for 21 h, referred to as long and short burn-in tests in this study. For burn-in tests, these two extreme voltage conditions were chosen based on the MIL-PRF-32535A standard. After burn-in tests, the MLCCs were cooled to room temperature without maintaining the electric field.

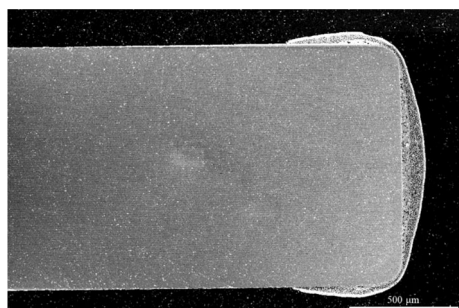


Figure 3 SEM image of BME X7R MLCC were used in this study.

Thermal stimulated depolarization current (TSDC) is a powerful technique for studying the relaxation kinetics of polarizable defects [7, 18–20], and it was used to investigate the effect of the short and long burn-in tests on ionic space charge development, both intergranular (ionic charge pile up within individual grains) and transgranular (ionic transportation beyond each grain). After short and long burn-in tests, TSDC was performed on screened samples; samples were then heated at a constant heating rate $\beta = 5^\circ\text{C}/\text{min}$, and the leakage current from depolarization of the relaxing defects was measured with a HP 4140b PA meter. Temperature data were collected using an HP 3478A multimeter, and the Itemp program was used to write data acquisition and device control. Under open-circuit conditions, the noise level measured in the experimental setup was in the pA range at 150°C .

Highly accelerated lifetime testing (HALT) was used to investigate the effect of burn-in tests on BME MLCCs failure rates. HALT was performed on 17 pristine and screened MLCCs under isothermal conditions of 135°C with a DC field ranging from $6 \times V_r$ to $7.5 \times V_r$. Each MLCC's failure time is defined by its electrical breakdown. Reliability Python library was used for failure statistical analysis [21].

Results and discussion

A burn-in test can lead to electromigration of oxygen vacancies that accumulate into metastable ionic space charge regions, and these in turn reduces the reliability of MLCCs by compromising the double Schottky barriers at the grain boundaries and electrode interfaces. TSDC measurements confirmed intergranular and transgranular ionic space charge accumulation after burn-in tests. TSDC spectrums are composed of two or three overlapped peaks within the recorded temperature window which appear as a broad and wide peak (Fig. 4). Each TSDC spectrum was deconvoluted to two or three relaxation peaks with different origin and the physical origin of each peak was identified by studying the dependence of temperature corresponding to the peak maximum (T_{max}) and its dependence on the electric field while heating at a constant rate. T_{max} decreases when the relaxation current is associated with trapped charges and increases when space charge is the physical origin of TSDC current [18, 19, 22, 23]. The first peak,

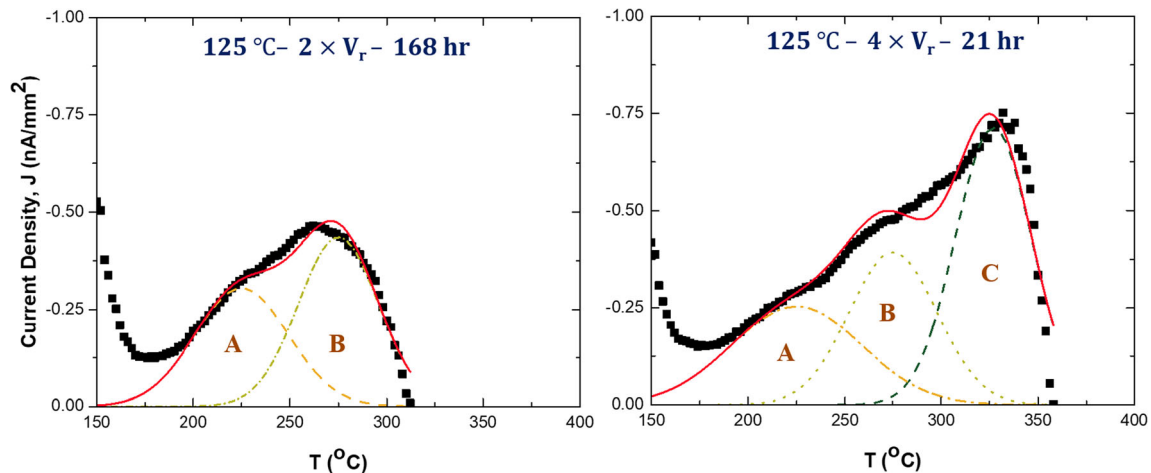


Figure 4 Effect of short and long burn-in tests on oxygen vacancies electromigration in BME X7R MLCCs.

peak A, appears at temperatures around 225 °C which is speculated to be thermal relaxation caused by modulated oxygen vacancy structures ($V_O^{\bullet\bullet} + e^- + Ti^{+4} \rightleftharpoons Ti^{+3} + V_O^{\bullet\bullet}$). The second peak, peak B, emerges at temperatures around 265 °C related to intergranular oxygen vacancy electromigration. The third peak, peak C, occurs at temperatures around 330 °C, which originated from transgranular oxygen vacancy electromigration and was only observed in samples that were screened with the short burn-in test. These oxygen vacancies electromigration can weaken the protection effect of double Schottky barriers at the grain boundaries and electrode interfaces which eventually reduces MLCCs lifetime.

The reduction in MLCCs lifetime was confirmed by comparing the mean time to failure (MTTF) and standard deviation (SD) values of samples before and after burn-in tests (Table 1). Although the MTTF did not change significantly (dropped up to 18%) after burn-in tests, the SD values increased up to 130 percent indicating that the TTF data are spread out, raising concerns about the consistency, predictability, and quality of BME MLCCs for applications requiring higher levels of reliability. Two-parameter Weibull distribution was used to analyze time-to-failure

(TTF) data obtained from HALT in different conditions. The distribution function can be written as

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\alpha}\right)^\beta\right)$$

where t is the failure time, α is the scale parameter, and β is a shape parameter corresponding to the slope of the Weibull probability plot. $\beta < 1$, $\beta = 1$, and $\beta > 1$ correspond to the infant mortality, useful lifetime, and wear-out parts of the hazard rate curve, respectively [24, 25].

The Weibull distribution of TTF data for $6 \times V_r$ and $7 \times V_r$ at 135 °C shows that pristine MLCCs have a unimodal distribution, whereas screened MLCCs with a burn-in test have a bimodal distribution. A bimodal distribution is formed by combining two two-parameter Weibull distributions, which represents a weak or freak population of failures within the overall failure distribution. Figure 5 demonstrates the presence of a freak population of screened MLCCs caused by oxygen vacancies electromigration during the burn-in test, which was revealed by TSDC measurements. The Weibull distribution of TTF data for $7.5 \times V_r$ at 135 °C appears that pristine samples also have a bimodal distribution due to aggressive HALT conditions, even though a freak population is still smaller than screened samples. TTF data from

Table 1 MTTF (SD) of commercial BME X7R MLCCs in different HALT conditions measured in hrs

		135 °C–300 V	135 °C–350 V	135 °C–375 V
Pristine samples		119 (10)	36 (7)	16 (7)
Screened samples	Long burn-in	100 (23)	33 (9)	17 (7)
	Short burn-in	107 (22)	35 (16)	13 (8)

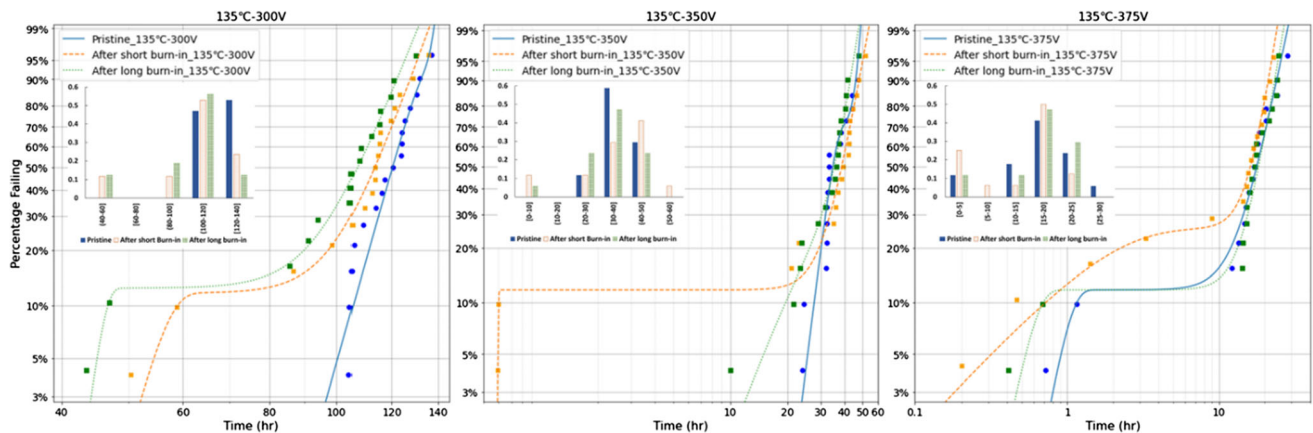


Figure 5 Weibull plot of pristine and screened sampled with short and long burn-in tests under different HALT conditions.

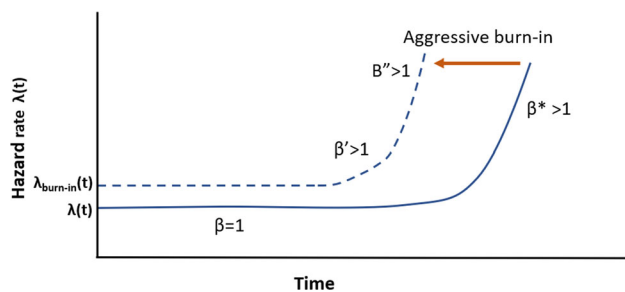


Figure 6 Schematic of hazard rate curve of MLCCs before (solid) and after (dash) short burn-in test.

screened samples with a short burn-in test for the same HALT condition clearly demonstrate that burn-in test increases a freak population and reduces the minimum TTF.

The similarity in Weibull distribution slope values between pristine MLCCs and the main population of screened MLCCs with a burn-in test suggests that the failure mechanism is unchanged and associated with oxygen vacancy migration. Furthermore, the slope parameter of the weak population of failures is greater than 1 ($\beta' > 1$), indicating that the early failures are not infant mortalities, and the burn-in test has not been beneficial in detecting infant mortalities and has only reduced the lifetime of MLCCs, as schematically shown in Fig. 6.

Conclusions

The burn-in test is a screening procedure used to eliminate weak components with a high likelihood of infant mortality and to produce uniform components for applications demanding higher levels of

reliability. We demonstrated that the costly burn-in test may be ineffective in identifying infant mortality failures, and it reduces the reliability and lifetime of BME MLCCs through intragranular and transgranular electromigration of oxygen vacancies which may not relax after the burn-in test. These oxygen vacancies electromigration creates a weak population of BME MLCCs that may fail much sooner than expected, resulting in a subsystem or system failure.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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