Difference between 85 °C/85 %RH accelerated life test and pressure cooker test on copper/epoxy bonding

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Keywords— *epoxy encapsulation, reliability, humidity, pressure cooker*

Abstract

The reliability of copper/epoxy bonding is crucial for the performance of power modules used in high-demand applications such as electric vehicles and renewable energy systems. This study investigates the degradation mechanisms and failure modes of copper/epoxy bonding under two accelerated life testing conditions: 85 °C/85 %RH and pressure cooker test (PCT). The bonding strength was measured at 0 hours, 240 hours, 500 hours, and 1000 hours for the 85 °C/85 %RH test, and at 0 hours and 96 hours for the PCT. Results showed a gradual decline in bonding strength for the 85 °C/85 %RH test, with values decreasing from 14.90 MPa to 13.34 MPa over 1000 hours. In contrast, the PCT conditions led to a more pronounced reduction in bonding strength from 14.90 MPa to 10.70 MPa in just 96 hours. SEM analysis of the fracture surfaces revealed that before any reliability tests, fractures primarily occurred within the epoxy layer. After the reliability tests, fractures shifted to the interface, indicating the weakening of the bonding interface. These findings indicate that the 85 °C/85 %RH test and PCT have distinct effects on copper/epoxy bonding, with the PCT causing significantly greater degradation. Therefore, industries should not regard these two tests as equivalent.

1 Introduction

The reliability of copper/epoxy bonding is a critical factor in the performance and longevity of electronic power modules, which are increasingly used in high-demand applications such as electric vehicles, renewable energy systems, and advanced robotics [1-4]. The push for miniaturization and enhanced performance of these modules has led to the widespread adoption of epoxy encapsulation over traditional gel encapsulation methods due to its superior mechanical and thermal properties [5,6]. However, despite the advancements in epoxy material technology, failures in power modules still persist, often attributed to the complex interfacial interactions between the encapsulation epoxy and the copper substrate [7-10].

Due to the prolonged duration required for the 85 °C/85 %RH test, which can extend up to 1000 hours or more, industries often use the pressure cooker test (PCT) as a substitute for evaluating product reliability. The PCT offers a significantly shorter test duration, typically around 96 hours, by subjecting samples to elevated temperature, humidity, and pressure simultaneously. This accelerated testing method is assumed to induce similar degradation mechanisms as the 85/85 test, leading to the belief that PCT and 85/85 provide comparable insights into the long-term performance of copper/epoxy bonding under harsh environmental conditions. Consequently, PCT has become a popular choice for rapid reliability assessments in industrial settings.

However, our observations and experimental data suggest that significant differences exist between the reliability evaluation results obtained from PCT and the 85/85 test. The distinct environmental stresses and durations of these tests appear to affect the degradation mechanisms differently. This discrepancy indicates that PCT may not always accurately replicate the conditions and outcomes of the 85/85 test. Therefore, our primary objective in this study is to investigate these discrepancies and understand the distinct effects that these two tests have on copper/epoxy bonding. By examining the differences in degradation mechanisms and bonding strength, we aim to provide a clearer understanding of how each test impacts the reliability of the bond. This knowledge will help refine testing protocols and ensure more accurate reliability assessments for industrial applications, leading to the development of more robust and reliable power modules.

2 Experiment

2.1. Materials and encapsulation packages

In this study, we utilized real encapsulation packages to ensure the relevance and applicability of our findings. The packages measured 12.5 mm × 12.5 mm × 3.3 mm, featuring a 1.3 mm thick encapsulation layer of epoxy resin over a C1020 oxygen-free copper substrate (Fig. 1 (a)). The primary focus was on the reliability of the interface between the copper substrate and the encapsulation epoxy; thus, no die-attach or wire bonding was performed in this work.

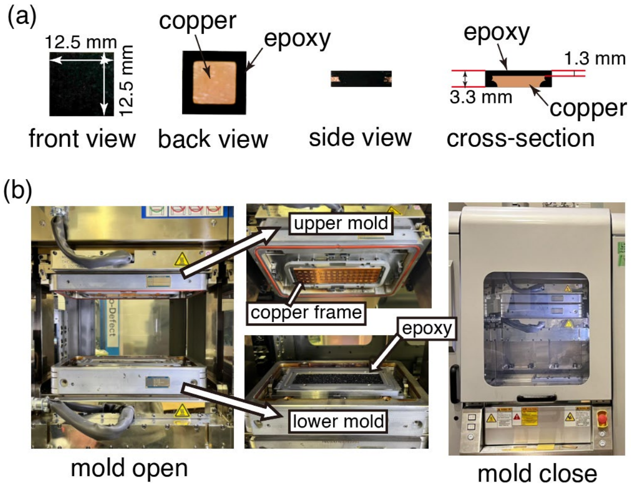

Fig. 1. (a) Images of a package; (b) Images of the upper mold and lower mold.

Table 1. Materials properties of the epoxy

Appearance (standard)	black liquid/white liquid
Glass transition temperature	224 ℃
Flexural modulus	10 GPa
Flexural strength	102 MPa
Linear expansion coefficient	15 ppm/℃
Volume resistivity	$1.0\times10^{16}\Omega\cdot$cm

Prior to the encapsulation process, the copper substrates underwent ultrasonic cleaning using ethanol to remove any contaminants. We selected a commercialized epoxy resin for encapsulation. This epoxy resin was chosen for its high glass transition temperature (Tg) , low linear expansion coefficient and enabling good workability. Besides, this is a two-part heat-curing epoxy resin. Table 1 presents the details of this epoxy.

The encapsulation process was performed using a face-down compression molding machine (PMC1040, TOWA) (Fig. 1 (b)) [11]. During the molding process, the epoxy resin was placed in the lower mold, preheated to 175 °C, while the copper substrate was secured in the upper mold using vacuum suction. The molds were then closed, applying a pressure of 3 MPa for 300 seconds to ensure proper encapsulation. Following the molding, the encapsulated substrates were cured at 215 °C for 5 hours in an oven to ensure complete polymerization and stability of the epoxy layer. Finally, the encapsulated copper frames were separated using an automatic dicing saw, resulting in the individual encapsulated packages ready for reliability testing.

2.2 Reliability test

To evaluate the reliability of the copper/epoxy bonding under different environmental stress conditions, two accelerated life tests were conducted: the 85 °C/85 %RH test and the pressure cooker test (PCT) presented in Table 2. These tests were designed to simulate the harsh conditions that the power modules might encounter during their operational lifetime and to understand the degradation mechanisms affecting the bonding interface.

Table 2. Reliability tests conditions.

Test name	Conditions	Test time
High temperature and high humidity storage test	85 ℃, 85%RH	0, 240, 500, 1000 h
Pressure cooker test (PCT)	121 ℃, 100 %RH, 2 atm	0, 96h

For the 85 °C/85 %RH accelerated life test, the encapsulated packages were exposed to a controlled environment with a temperature of 85 °C and a relative humidity of 85%. This test aimed to simulate the effects of prolonged exposure to high temperature and humidity, conditions that are commonly encountered in various operational environments. The test durations were set at 240 hours, 500 hours, and 1000 hours. The samples were periodically removed at these intervals to assess the impact of the environmental conditions on the bonding strength and to analyze any changes at the interface.

The pressure cooker test (PCT) was conducted to further accelerate the aging process by subjecting the samples to high temperature, high humidity, and high pressure simultaneously. The test conditions were set at 121 °C, 100% relative humidity, and 2 atm pressure. The duration for this test was fixed at 96 hours. This combination of high temperature and pressure aimed to induce rapid degradation, providing insights into the failure mechanisms that could occur over extended periods in real-world conditions.

After each reliability test, the bonding strength of the samples was evaluated using shear testing methods. Additionally, the interface and fracture surfaces were examined using techniques such as Scanning Electron Microscopy (SEM), to gain a detailed understanding of the changes in the bonding interface and the degradation processes occurring under different test conditions.

2.3 Bonding strength evaluation

To evaluate the impact of the reliability tests on the bonding strength between the encapsulation epoxy and the copper substrate, a systematic shear testing method was employed. Given the package's shape, directly measuring the bonding strength posed a challenge. To overcome this, we developed a unique approach that involved creating a 4 mm × 4 mm cubic island shape on the substrate using a laser decapsulation system (PL201, Nippon Scientific). Fig. 2 (a) shows this process.

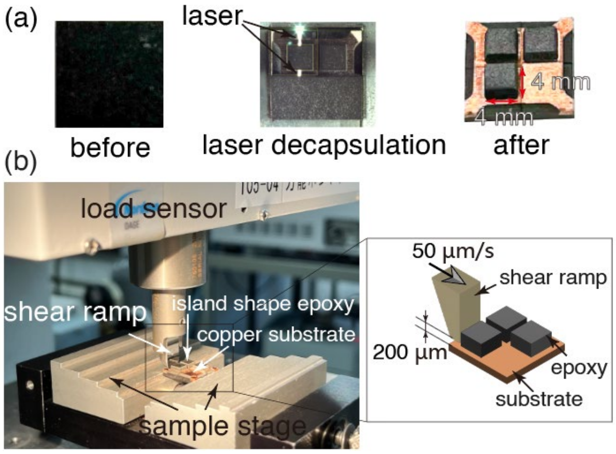

Fig. 2. (a) Images of the package before and after the decapsulation; (b) Image and illustration of the setups for the shear test.

The process began by removing some of the epoxy to expose the copper substrate and form the cubic island. The bonding strength was then measured by shearing this island-shaped epoxy using a shear tester (Dage 4000, Nordson). During the shear test, the copper substrate was securely fixed on the sample stage. The shear ramp applied a predefined height and speed until the epoxy fractured, and the maximum shear force was recorded (Fig. 2(b)). The bonding strength was calculated by dividing the maximum shear force by the contact area of the epoxy on the copper substrate.

For each reliability test condition, seven samples were tested to ensure statistical relevance. The average bonding strength was calculated from these measurements to provide a comprehensive understanding of how different test conditions affected the epoxy/copper bond. This method allowed for precise quantification of the bonding strength changes induced by the accelerated life tests, providing valuable insights into the reliability of the encapsulated packages under various environmental stress conditions.

3 Results and discussion

3.1 85 °C/85 %RH Accelerated Life Test

The bonding strength of the copper/epoxy interface [12] was evaluated under 85 °C and 85% relative humidity conditions at various time intervals: 0 hours, 240 hours, 500 hours, and 1000 hours (Fig. 3. (a)). The results showed that bonding strength remained relatively stable over time, with no significant or drastic decline observed. [13,14]. Initially, the bonding strength was measured at 14.90 MPa. After 240 hours, the bonding strength slightly decreased to 14.37 MPa, indicating minor degradation. This trend continued with the bonding strength reducing to 13.37 MPa at 500 hours and further to 13.34 MPa at 1000 hours.

The slight reduction in bonding strength can be attributed to the prolonged exposure to high humidity, which may have facilitated moisture ingress into the epoxy, leading to hydrolytic degradation [15]. Additionally, the high temperature could have accelerated thermal oxidative degradation processes within the epoxy, weakening the bond over time. Thermal oxidative degradation plays a crucial role in this process. When the epoxy is exposed to high temperatures and humidity, the epoxy groups within the resin begin to decompose. This degradation occurs in two stages. Initially, the aliphatic C-H bonds oxidize, forming hydroperoxides. In the second stage, these hydroperoxides decompose into free radicals, leading to bond scissions and the formation of smaller volatile molecules. These processes reduce the structural integrity of the epoxy, weakening the bonding strength over time. This detailed mechanism explains why the bonding strength, although relatively stable, does exhibit a gradual decline under prolonged exposure to high temperatures and humidity [3]. The results indicate that while the bonding strength decreases under these conditions, the degradation rate is relatively slow, suggesting that the epoxy maintains a considerable portion of its integrity even after extended exposure.

3.2 Pressure Cooker Test (PCT)

Under the pressure cooker test conditions of 121 °C, 100% relative humidity, and 2 atm pressure, the bonding strength of the copper/epoxy interface was evaluated at 0 hours and after 96 hours (Fig. 3. (b)). Initially, the bonding strength was 14.90 MPa. After 96 hours, a significant decrease in bonding strength was observed, with the value dropping to 10.70 MPa.

The more pronounced reduction in bonding strength under PCT conditions can be attributed to the combined effects of high temperature, high humidity, and high pressure, which likely accelerated the degradation mechanisms within the epoxy. The elevated pressure promotes moisture ingress and diffusion through the epoxy, leading to more severe hydrolytic degradation. Furthermore, the high temperature under these conditions could enhance thermal oxidative degradation, breaking down the epoxy network more rapidly and weakening the bond with the copper substrate.

Theoretical analysis of the degradation mechanisms can be explained using Fick's laws of diffusion and the Arrhenius equation. According to Fick's First Law: $J = -D\nabla\varphi$, where J is the diffusion flux, D is the diffusion coefficient, and $\nabla\varphi$ is the concentration gradient. Fick's Second Law provides the time-dependent change in concentration: $\frac{\partial\varphi}{\partial t} = D\nabla^2\varphi$, The diffusion coefficient D is temperature-dependent and can be described by the Arrhenius equation: $D = D_0 e^{-\frac{E_a}{RT}}$, where D_0 is the pre-exponential factor, E_a is the activation energy, R is the gas constant, and T is the absolute temperature. These equations collectively explain how the increase in temperature during PCT accelerates the diffusion of moisture and degradation agents into the epoxy, leading to a reduction in bonding strength. Additionally, Graham's law of diffusion explains the pressure dependence of the diffusion rate: $\frac{r_1}{r_2} = \sqrt{\frac{M_2}{M_1}}$, where r_1 and r_2 are the diffusion rates, and M_1 and M_2 are the molar masses of the diffusing substances. Increased pressure enhances the activation energy, further accelerating the degradation process.

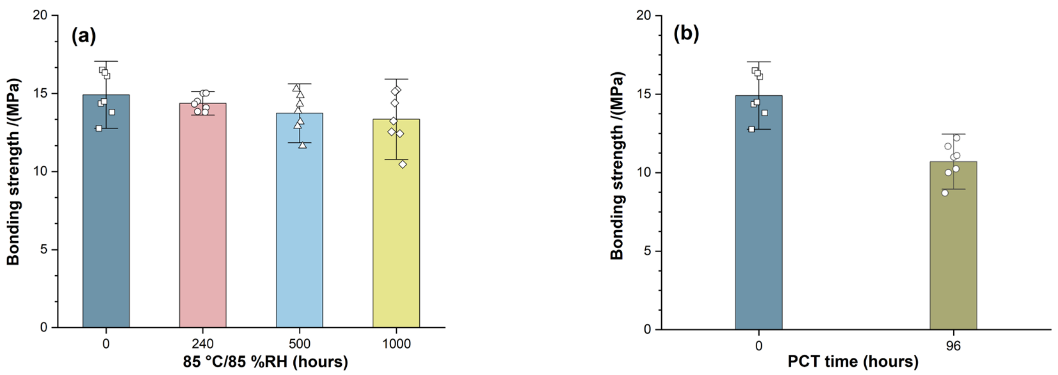

Fig. 3. The bonding strength results for (a) 85 °C/85 %RH, (b) PCT.

In industrial production processes, it is crucial not to equate the 85/85 test with the PCT test. The aging processes and degradation mechanisms involved in these tests are fundamentally different. Understanding and recognizing these differences is essential for accurate reliability assessments and ensuring the robustness of epoxy-encapsulated power modules in various operational environments.

3.3 SEM analysis of fracture surfaces

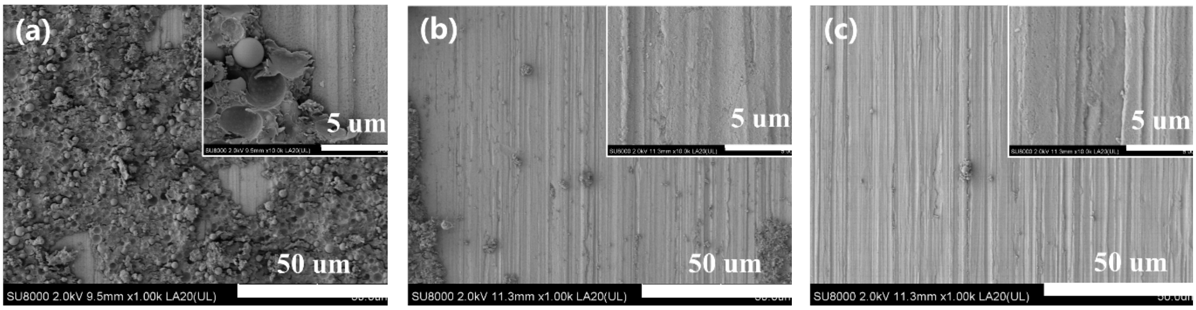

Fig. 4. SEM images of the fracture surface of the copper side (a) before reliability tests, (b) after 1000 h of 85 °C/85 %RH, (c) after 96 h PCT.

To further investigate the degradation mechanisms, SEM images of the fracture surfaces on the copper side were taken before and after the reliability tests. Before any reliability tests (Fig. 4. (a)), the fracture predominantly occurred within the epoxy layer, indicating strong initial bonding at the copper/epoxy interface.

After 1000 hours of the 85 °C/85 %RH test (Fig. 4. (b)), the fracture began to occur at the interface between the copper and epoxy. This shift in the fracture location suggests that the prolonged exposure to high humidity and temperature weakened the bonding interface, making it the primary failure point.

In contrast, the SEM images after 96 hours of the PCT (Fig. 4. (c)) showed that the fracture also occurred at the interface. The severe conditions of the PCT, including high temperature, humidity, and pressure, likely accelerated the degradation of the bonding interface, resulting in a light pronounced failure at the interface compared to the 85 °C/85 %RH test.

4 Conclusions

This study highlights the impact of different environmental stress conditions on the reliability of copper/epoxy bonding in power modules. The 85 °C/85 %RH test demonstrated a gradual decline in bonding strength, primarily due to moisture ingress and thermal oxidative degradation, indicating the epoxy's resilience under moderate environmental stress over extended periods. Conversely, the PCT induced a more significant and rapid decline in bonding strength, emphasizing the combined effects of high temperature, humidity, and pressure in accelerating degradation processes. SEM analysis provided visual confirmation of these degradation mechanisms, with notable surface oxidation and roughening observed, especially under PCT conditions.

These findings suggest that the 85/85 test and PCT should not be considered equivalent in reliability evaluations. They distinctly affect the aging process and degradation mechanisms of copper/epoxy bonding. Consequently, it is essential for industries to acknowledge these differences to perform accurate reliability assessments and ensure the durability of epoxy-encapsulated power modules in diverse operational environments.

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