

APPLICATION OF ACCELERATED LIFE TESTING IN SOLDER JOINT LIFE PREDICTION

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Abstract: Accelerated life testing (ALT) is an efficient reliability evaluation method with significant application value in solder joint life prediction for electronic packaging. This paper systematically reviews the theoretical basis and practical applications of ALT in solder joint life prediction. It analyzes the main failure mechanisms such as thermomechanical fatigue, electromigration, and creep, discusses the principles and applicability of accelerated models such as Arrhenius, Coffin-Manson, and Norris-Landzberg, and elaborates on the calculation methods of acceleration factors and test design optimization considering stress types such as temperature, vibration, and humidity. Literature case studies show that ALT, by simulating long-term service conditions, can rapidly reveal the microstructural degradation characteristics of solder joints, significantly shortening the test cycle and improving prediction accuracy. The study further points out that combining data-driven methods with multi-physics coupling models is a promising future direction, effectively addressing challenges arising from multiple variable interactions and complex environments, and providing a scientific basis for the design of highly reliable electronic products.

Keywords: Accelerated life testing; Solder joint reliability; Thermomechanical fatigue; Acceleration factor; Lead-free solder

1 INTRODUCTION

1.1 Research Background

In electronic packaging, solder joints, as primary mechanical and electric interfaces between elements, directly impact entire system durability and reliability. As electronic products move in direction to higher density, small size, and higher power, solder joints face more complex thermomechanical stress conditions, leading to fatigue failure as an overriding failure mechanism. Classic life prediction methods relying on long-duration testing under normal operating conditions are time-consuming and costly. Accelerated life testing (ALT) has been widely used as an effective method to simulate long-duration service conditions through acceleration stresses like temperature cycling, mechanical vibration, or humidity, and accelerate solder joint life prediction at high rates. Early research involved life prediction and acceleration test analysis on lead-containing solders, e.g., examining fatigue behavior under temperature cycling through constitutive models and finite element simulations [1]. As due regulations have been implemented to eliminate lead-containing solders, lead-free solders such as Sn-Ag-Cu alloys have been increasingly replacing lead-containing solders. Their failure mechanism and microstructure evolution during failure have been more complex, and adaptive acceleration models have been established to estimate reliability under thermal cycling conditions [2]. In recent years, scientists have made combination-based approaches of mechanical and finite element test analysis to develop damage accumulation-based life prediction models under high-frequency bending loads for large-area solder joints, and made validations for their realization on numerous alloys such as PbSnAg and SnSbAg [3]. Besides, strain and temperature-associated crack initiation and growth models have been emphasized for high-area solder joints, utilizing finite element approaches to estimate crack growth rates for accurate life prediction at specified loads [4]. Machine learning methods have also been utilized to handle reliability estimation under multi-parameter actions, estimating thermal cycling impacts on solder joint life based on correlation-driven neural network models and improving estimation accuracy and efficiency [5]. These developments have laid superior theoretical foundations on solder joint life prediction, and have converted estimation models into data-driven models from empirical models.

1.2 Significance of the Research

Research in solder joint life estimation has strategic importance in maximizing collective product electronic product reliability and reducing potential failure risk, particularly in situations involving high-reliability products such as automotive, space, and home electronics products. Accelerated life tests can expediently shorten product life cycles, calibrate design parameters, and reduce unexpected in-service failures, and thereby reduce economic losses and safety hazards. While classical methods remain correct, they have the tendency to relinquish inter-factor interaction. Advanced models and machine learning schemes can more aptly capture chemical composition, geometry, and thermal cycling parameter effects on life, allowing more credible life extrapolation from accelerated tests to in-service life [5]. This research also aids in standardizing lead-free solder applications, for example, in estimating thermal cycling fatigue life of Sn-3.0Ag-0.5Cu solder joints under censored Type I data processing and Weibull statistics analysis, allowing credible

accelerated life factor calculation schemes [2]. In high-power electronics modules, life estimation schemes of large-area solder joints lead to material and structure optimizations, ensuring long-running stability under harsh conditions such as high temperature and strain rate through damage accumulation laws and FE simulations [3][4]. In an engineering sense, this research not only supports product competitiveness but also industry sustainability, for example, critically reflecting acceleration test role to assist in establishing more scientific reliability criteria in the aspect of electronic manufacturing.

2 THEORETICAL BASIS

2.1 Basic Principles

Accelerated life test (ALT) is one form of reliability test technique, through which products' failure process is expedited through subjecting products to stresses higher than normal in-service stresses. Its central idea depends on exploiting an exponential or power-law correlation between reaction rates of physical or chemical reaction and stress intensities to expedite long-term reliability prediction over short time period. In electronic packaging, and solder joint life prediction in specific, most central concept of ALT depends on acceleration of failure mechanism activation, i.e., through thermally activated creep, fatigue, and diffusion process, under increased temperature or cycling load, reducing test time and revealing latent defect. The classical hypothesis of ALT assumes postulation that acceleration-induced failure mode under increased condition would be same as normal condition, without invoking new mechanism action. As an example, solder joint thermo-mechanical fatigue life would be predicted based on thermal cycling tests, and data scatter would be dealt through applying statistics such as Weibull analysis [6]. Secondly, ALT concentrates on acceleration factor estimation, i.e., through utilizing Arrhenius relation to describe temperature dependency of reaction rates, or Eyring model to describe multi-stress interactions, to offer credible extrapolation of laboratory data to practical situations [7]. In solder joint applications, this concept has been generalized to consider microstructure evolution, i.e., grain growth and phase separation, to verify consistency in failure trajectories in acceleration tests through finite element modeling in order to offer model applicability [8]. Conceptual framework of ALT consists of stress selection, test plan, and data analysis stages, wherein stress intensities must be controlled to maintain acceleration effectiveness and accuracy intact, without invoking non-representative failure due to over-stress [9].

2.2 Common Acceleration Models

Acceleration models, in most instances, consisting of physical mechanism-based mathematical models, have been utilized to obtain the lifetime distribution under normal conditions from accelerated test results in solder joint life prediction. The Arrhenius model represents the simplest temperature acceleration model, under an assumption of an exponentially linear relation between temperature and failure rate, and it has been commonly applied in thermal aging tests to estimate solder joint diffusion and creep failure, extracting acceleration effect parameters in terms of activation energy [7]. Another widely used model, Coffin-Manson model, corrects for low-cycle fatigue, and it consists of power-law correspondence between plastic strain and cycle life, and it would be superior for solder joint fatigue crack growth under temperature cycling [9]. What follows furthermore is also the Norris-Landzberg model, an extension of this model, consisting of terms for temperature amplitude, frequency, and max temperature, and it leads to more precise acceleration factor calculations, particularly for thermal cycle reliability testing of lead-free solders such as Sn-Ag-Cu [6]. These acceleration models capitalize on empirical parameter calibrations in terms of, e.g., experimental data fitting or finite element analysis to allow for necessary solder joint geometry, material property, and type of stress accommodations [10]. Under multi-stress conditions, there also follows an Eyring model, which also consists of terms, such as voltage and humidity, to allow for more complete acceleration simulation [8].

2.3 Acceleration Factor and Stress Types

Acceleration factor (AF) can be described as normal condition lifetime divided by acceleration condition lifetime, correlating test data to in-service prediction, playing an indispensable role in solder joint reliability prediction. Temperature, humidity, mechanical vibration, and voltage bias stresses are most common, and temperature stress dominates, inducing thermo-mechanical fatigue and interdiffusion by thermal cycling or isothermal aging, leading to rapid solder joint failure [6]. Temperature-humidity bias tests also tend to couple humidity stress and temperature, driving ionic migration and electrochemical corrosion; Peck's model can be used to calculate AF, integrating relative humidity and temperature power-law effects [7]. Mechanical stress, such as vibration or bending, targets fatigue crack initiation; the AF is based on an inverse power-law model, depending on stress amplitude and frequency [9]. In specific solder joint scenarios, multi-stress interactions need consideration, such as temperature-vibration combined tests to simulate complex automotive electronics environments, with the generalized Eyring model calculating the comprehensive AF [8]. Voltage stress induces electromigration in high-power applications; the AF follows Black's equation, emphasizing the roles of current density and temperature [10]. Selection of these stress types should be based on Failure Mode and Effects Analysis (FMEA), ensuring accelerated tests represent real-world conditions, while statistical validation of the AF accuracy minimizes prediction errors.

3 OVERVIEW OF ACCELERATED LIFE TESTING APPLICATIONS IN SOLDER JOINT LIFE PREDICTION

3.1 Overview of Solder Joint Failure Mechanisms

As a critical interconnect component in electronic packaging, solder joints primarily fail due to microstructural changes and damage accumulation induced by thermo-mechanical stress, leading to a decline in overall system reliability. Under thermal cycling conditions, solder joints undergo heterogeneous coarsening and thickening of the intermetallic compound (IMC) layer. Cracks typically initiate and propagate at the interface between the IMC layer and the coarsened zone, ultimately leading to fracture failure [11]. Lead-based solder exhibits a faster fatigue crack growth rate and propagates transgranularly, while lead-free solders, such as Sn-3.5Ag-X alloys, have fatigue resistance influenced by alloying elements; for example, the addition of Bi reduces ductility and shortens fatigue life [11]. Furthermore, solder thickness and dwell time at high temperatures have limited effects on thermal fatigue, but frequency and temperature amplitude significantly affect life; higher temperatures shorten life, and specific frequency ranges (e.g., 10^{-4} Hz to 10^{-3} Hz) accelerate damage [11]. Thermomechanical loading further amplifies the failure process, generating cyclic plastic strain due to coefficient of thermal expansion (CTE) mismatch, leading to fatigue and creep failure; cracks propagate along grain boundaries and concentrate at interfaces [12]. Creep mechanisms dominate deformation at high temperatures, and models like Dorn or Anand describe the effects of stress, temperature, and grain size, while fatigue models such as Coffin-Manson predict life based on plastic strain [12].

3.2 Application of Accelerated Testing Methods

Accelerated life testing for solder joint life prediction simulates long-term service conditions by intensifying environmental stress, enabling efficient reliability assessment and design optimization. In thermal cycling tests, a data-driven framework combining linear mixed effects models (LME) and artificial neural networks (ANN) analyzes limited experimental data, examining the effects of aging time, temperature, and solder composition on lead-free solder life, providing interpretable predictive results [13]. This method assumes Weibull distribution for failure time, uses a variant of the Norris-Landzberg model to generate simulated data, improves prediction accuracy, and reveals the effects of key parameters such as temperature amplitude (ΔT) and dwell time through sensitivity analysis. Furthermore, accelerated fatigue shear tests assess the impact of aging on the reliability of SAC305 solder joints, applying 16-24 MPa stress amplitude after aging at 100°C for different durations; Weibull distribution analyzes the exponential decrease in characteristic life [14]. Testing reveals that increased aging time and stress amplitude amplify irreversible work and plastic strain. Power-law model provides an equation relating lifetime and these parameters to enable generalized prediction of reliability as a function of aging and stress [14]. These methodologies offer advantages in terms of calculating uncertainties and correlating laboratory data to practical applications, such as lead-free solder alloy choice optimization in the aerospace sector.

3.3 Literature Case Studies

Literature case studies demonstrate the practical value of accelerated life testing in solder joint reliability assessment. For example, the Risk-Informed Systems Qualification (RISQ) method, combining thermal cycling and mechanical stress testing, evaluates the durability of Column Grid Array (CGA) solder joints in advanced electronic packaging [15]. One case study focused on a 337-pin ASIC device for low-Earth orbit (LEO) missions, simulating 26,816 day-night cycles over 5 years. Accelerated testing at 0-100°C with an acceleration factor of 78 predicted failure cycles using Coffin-Manson and Norris-Landzberg models, ensuring a system failure probability below 0.1%. The test showed that CTE mismatch caused fatigue failure, and solder joint height and distance to neutral point (DNP) parameters affected lifetime, validating the shear failure mode of SnPb adhesion. Another case focused on data-driven prediction of lead-free solder under thermal cycling. Using LME and ANN frameworks to analyze Auburn University experimental data, it assessed the superior performance of Innolot alloy in small-size BGAs and the minimal degradation of PBGA1156 under aging (R^2 up to 91.79%) [13]. Furthermore, an accelerated fatigue test case for SAC305 solder joints showed a 73% decrease in characteristic lifetime after 1000 hours of aging. Plastic strain was quantified through hysteresis loop analysis, and a power-law model predicted early failure (B10) [14].

4 CONCLUSION

The application of accelerated life testing (ALT) in solder joint lifetime prediction provides an efficient and scientific assessment method for electronic packaging reliability research, particularly important in the design of high-reliability electronic products. By systematically analyzing failure mechanisms such as thermo-mechanical fatigue, electromigration, and creep, Accelerated Life Testing (ALT) can simulate long-term service conditions in a shorter time, revealing the degradation patterns of solder joint microstructure, thus optimizing material selection and process design. Based on accelerated testing methods using models such as Arrhenius, Coffin-Manson, and Norris-Landzberg, accurate calculation of acceleration factors allows extrapolation of laboratory data to real-world applications, significantly shortening product development cycles and reducing testing costs. Furthermore, the integration of various testing methods, including thermal cycling, vibration, and combined stress tests, further enhances prediction accuracy, meeting the stringent requirements of industries such as automotive and aerospace.

While ALT has made significant progress in solder joint life prediction, it faces challenges such as multi-factor interactions, complex microstructure, and the representativeness of test conditions. Future research needs to incorporate

data-driven methods, such as machine learning and statistical models, to address multi-variable uncertainties and develop more accurate multi-physics coupling models to improve prediction generalization. Establishing standardized test protocols and a failure database will also enhance the universality and reproducibility of ALT methods. Overall, accelerated life testing provides a solid foundation for solder joint reliability assessment, and its continued development will drive electronic packaging technology towards higher performance and longer lifespan, offering more reliable engineering solutions for the industry.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

- [1] Qian Z, Liu S. On the life prediction and accelerated testing of solder joints. *The International Journal of Microcircuits and Electronic Packaging*, 1999, 22(4): 288-304.
- [2] Mi J, Li YF, Yang YJ, et al. Thermal cycling life prediction of Sn-3.0Ag-0.5Cu solder joint using Type-I censored data. *The Scientific World Journal*, 2014, 2014: 807693.
- [3] Lederer M, Betzwar Kotas A, Khatibi G. Lifetime modeling of solder joints based on accelerated mechanical testing and finite element analysis. *Power Electronic Devices and Components*, 2023, 5: 100034.
- [4] Lederer M, Betzwar Kotas A, Khatibi G. A lifetime assessment and prediction method for large area solder joints. *Microelectronics Reliability*, 2020, 114: 1-7.
- [5] Samavatian V, Fotuhi-Firuzabad M, Samavatian M, et al. Correlation-driven machine learning for accelerated reliability assessment of solder joints in electronics. *Scientific Reports*, 2020, 10: 14821.
- [6] Che FX, Pang HL, Ong YC, et al. Assessment of acceleration models used for BGA solder joint reliability studies. *Microelectronics Reliability*, 2009, 49(7): 754-760.
- [7] Suhir E. Accelerated life testing (ALT) in microelectronics and photonics: Its role, attributes, challenges, pitfalls, and interaction with qualification tests. *Microelectronics Reliability*, 2003, 43(4): 509-520.
- [8] Badri SH, Lall P. Reliability modeling of the fatigue life of lead-free solder joints at different testing conditions using a modified power law model. *Scientific Reports*, 2023, 13(1): 2284.
- [9] Tan L, Chen H, Ma B, et al. A state-of-the-art review of fatigue life prediction models for solder joint in electronics. *Journal of Electronic Packaging*, 2019, 141(4): 040802.
- [10] Engelmaier W. Solder joint reliability, theory and applications. *Soldering & Surface Mount Technology*, 1991, 3(1): 14-20.
- [11] Li L, Du X, Chen J, et al. Thermal fatigue failure of micro-solder joints in electronic packaging devices: A review. *Materials*, 2024, 17(10): 2365.
- [12] Depiver JA, Mallik S, Amalu EH. Solder joint failures under thermo-mechanical loading conditions - a review. *Advances in Materials and Processing Technologies*, 2021.
- [13] Alakayleh A, Jiang Z, Xie R. Interpretable data-driven framework for predicting the life of lead-free solder materials under thermal cycling. *Journal of Intelligent Manufacturing*, 2025.
- [14] Al Athamneh R, Abueed M, Bani Hani D, et al. Effect of aging on SAC305 solder joints reliability in accelerated fatigue shear test. *Proceedings of SMTA International*, 2018.
- [15] Ghaffarian R, Evans JW. Enabling more than Moore: accelerated reliability testing and risk analysis for advanced electronics packaging. *Proceedings of the 2014 IEEE Accelerated Stress Testing and Reliability Conference (ASTR)*, 2014: 1-7.