TEMPERATURE AND STRAIN-RATE DEPENDENT DAMAGE-BASED MODELS FOR LEAD-FREE SOLDER INTERCONNECTS

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ABSTRACT

Microelectronic packages with ball grid array (BGA) solder interconnects are subjected to thermomechanical load cycles during fabrication and throughout service life. The lead-free solder joints of BGA respond to both temperature and strain-rate depends on the exposed temperature cycles. Consequently, damage-based models are required for predicting accurately the reliability of the package. The analysis requires temperature and strain-rate dependent properties of the solder alloy and the solder/intermetallic compound (solder/IMC) interfaces. Solder/IMC interfaces of the solder interconnects have a high susceptibility to failure in Sn-4.0Ag-0.5Cu (SAC405) solder joints. The purpose of this research is to establish temperature and strain-rate dependent damage-based models for describing the failure process of solder interconnects. In this study, reliability temperature cycles with high heating and cooling ramps were used to examine the characteristic evolution of stresses and inelastic strains of the solder joints in the BGA package. A 3D finite element model of the BGA package under reflow cooling from 220 to 25 °C and subsequent temperature cycles between 125 to -40 °C was evaluated in predicting the damage initiation, propagation, and solder/IMC interface fracture process of the solder joints. Unified inelastic strain constitutive (Anand) model with optimized model parameters and the cohesive zone model was implemented to predict the creep-viscoplasticity effect of the bulk solder joint and the fracture of brittle solder/IMC interface. It was found that the most critical solder joint is located underneath the silicon die corner with the highest equivalent inelastic strain and von Mises stress under reflow cooling. As expected, the strain rate dependency of the damage model shows a faster inelastic strain rate which is 4×10^{-5} s^{-1} found in the critical solder joint after three temperature cycles with 900 second dwell time as compared to inelastic strain rate under reflow cooling. The accumulation of inelastic strain is confined to the small edge region at the solder/IMC interface at the board side of the assembly. Damaged location in the bulk solder occurs closer to the edge of the solder/IMC interface throughout the temperature cycles. Based on the parametric study, the higher ramp rate of 370 °C/min has resulted in greater inelastic strain accumulation compared to lower ramp rates of 11 and 22 °C/min in the solder joint with an inelastic strain rate of 1.5×10^{-3} s^{-1}. The validated finite element model with damage-based material response enables the fast generation of reliability data of the solder joints in newly designed BGA packages for competitive time-to-market of the product.

ABSTRAK

Pakej mikroelektronik dengan rangkaian tatasusunan grid bebola (BGA) bagi sambungan pateri saling hubungan mengalami kitaran beban termomekanik semasa fabrikasi dan juga sepanjang penggunaannya. Tindakbalas sambungan pateri bebas plumbum di dalam BGA terhadap kadar terikan dan suhu bergantung kepada kitaran suhu yang didedahkan. Oleh itu, model berasaskan kerosakan diperlukan untuk meramalkan kebolehpercayaan pakej secara tepat. Analisis memerlukan sifat kebergantungan suhu dan kadar terikan pateri aloi dan antara muka pateri/sebatian antara logam (pateri/IMC). Antara muka pateri/IMC saling hubung pateri mempunyai kerentanan yang tinggi untuk gagal dalam sambungan pateri Sn-4.0Ag-0.5Cu (SAC405). Tujuan penyelidikan ini adalah untuk menentukan model berasaskan kerosakan yang bergantung pada kadar suhu dan terikan bagi menggambarkan proses kegagalan sambungan pateri. Dalam kajian ini, kebolehpercayaan kitaran suhu pada tanjakan pemanasan dan penyejukan yang tinggi digunakan untuk meneliti evolusi ciri-ciri tegasan dan keterikan tidak anjal sambungan dalam pakej BGA. Model unsur terhingga 3D bagi pakej BGA di bawah penyejukan ulang aliran dengan julat suhu antara 220 hingga 25 °C dan kitaran suhu berturutan dengan julat suhu antara 125 hingga -40 °C dinilai untuk meramalkan permulaan kerosakan, perambatan kerosakan dan proses retakan antara muka pateri/IMC. Model konstitutif terikan tidak anjal (Anand) dengan parameter model yang dioptimumkan dan model zon jeleket dilaksanakan untuk meramalkan kesan rayapan-plastikvisko sambungan pateri pukal dan retakan rapuh antara muka pateri/IMC. Ia mendapati bahawa sambungan pateri yang paling kritikal adalah yang terletak di bawah sudut dai silikon dengan terikan tidak anjal dan tekanan von Mises yang paling tinggi di bawah penyejukan ulang aliran. Seperti yang dijangkakan, kebergantungan kadar terikan dengan kadar tanjakan bagi model kerosakan menunjukkan kadar terikan tidak anjal lebih tinggi iaitu $4x10^{-5}$ s^{-1} pada kawasan pateri kritikal selepas dikenakan tiga kitaran suhu dengan masa inap 900 saat berbanding dengan kadar terikan tidak anjal di bawah penyejukan ulang aliran. Penumpukan terikan tidak anjal tertumpu di kawasan pinggir yang kecil di antara muka pateri/IMC di bahagian tepi papan pemasangan. Lokasi kerosakan dalam pateri pukal berlaku dekat dengan pinggir antara muka pateri/IMC sepanjang kitaran suhu dikenakan. Berdasarkan kajian parametrik, kadar tanjakan yang lebih tinggi 370 °C/min mengakibatkan penumpukan terikan tidak anjal dalam sambungan pateri dengan kadar 1.5×10^{-3} s^{-1} berbanding dengan kadar tanjakan yang lebih rendah iaitu 11 dan 22 °C/min. Model unsur terhingga yang telah disahkan melalui tindak balas bahan berasaskan kerosakan membolehkan penjanaan kebolehpercayaan data bagi sambungan pateri yang lebih cepat ketika merekabentuk pakej BGA yang baharu dengan masa pasaran produk yang lebih kompetitif.

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LIST OF ABBREVIATIONS

3D - Three-dimensional
BGA - Ball grid array
B-K - Benzeggagh-Kenane
CTE - Coefficient of thermal expansion
CDM - Continuum damage model
CZM - Cohesize zone model
DBTSR - Ductile-to-brittle transition strain rate
ENIG - Electroless Nickel Immersion Gold
EDX - Energy dispersive X-ray
FCBGA - Flip-chip ball grid array
FE - Finite element
FESEM - Field emission scanning electron microscopy
FEA - Finite element analysis
FEM - Finite element model
FR-4 - Flame Retardant-4
IMC - Intermetallic compound
JEDEC - Joint Electron Device Engineering Council
LED - Light-emitting Diode
NSMD - Non-solder mask defined
PCB - Printed circuit board
R-T - Rice-Tracey
SAC - Sn-Ag-Cu
SAC405 - Sn-4.0Ag-0.5Cu
SMD - Solder mask defined
SMT - Surface mount technology
SDEG - Scalar stiffness degradation
SPT - Shear push test
TC - Temperature cycle
TR - Thermal shock
QUADSCRT - Quadratic nominal stress damage initiation criterion

LIST OF SYMBOLS

A - Pre-exponential factor for Anand model
a - Strain rate sensitivity of the hardening coefficient
D - Damage
d - Displacement
E - Young’s modulus
G_C - Critical strain energy release rate
G_I - Mode I strain energy release rate
G_{II} - Mode II strain energy release rate
G_{IC} - Mode I critical strain energy release rate
G_{IIC} - Mode II critical strain energy release rate
h_0 - Hardening coefficient for Anand model
k_p - Penalty stiffness
k_n - Cohesive element penalty stiffness in normal direction
k_s - Cohesive element penalty stiffness in the shear direction
m - Strain rate sensitivity of stress for Anand model
n - Strain rate sensitivity of saturation value for Anand model
N - Maximum normal stress for cohesive element
Q/R - Activation energy
S - Maximum shear stress for cohesive element
$\hat{s}$ - Deformation resistance saturation value for Anand model
s - Internal variable for Anand model
s^* - Saturation value of deformation resistance for Anand model
s_0 - Initial value of internal variable for Anand model
T - Temperature
T_L - Liquidus melting temperature
T_S - Solidus melting temperature
t_{dwell} - Dwell time
U_x - Displacement in X-axis
U_y - Displacement in Y-axis
U_z - Displacement in Z-axis

UR_x - Rotation about X-axis
UR_y - Rotation about Y-axis
UR_z - Rotation about Z-axis

Greek Symbols

$\dot{\varepsilon}_{in}$ - Inelastic strain rate
δ - Separation
δ_n - Normal displacement
δ^f - Separation at failure
δ_n^o - Onset displacement of damage under tension
δ_s^o - Onset displacement of damage under shear
δ_n^o - Separation of the interface under tension
δ_n^o - Separation of the interface under shear
δ_o - Damage initiation onset
η - Benzeggegh-Kenane mixed-mode parameter
τ_{13} - The shear stress in direction-13
τ_{23} - The shear stress in direction-23
σ_{33} - Normal stress at direction-33
σ_{vm} - von Mises stress
σ_y - Yield stress
ξ - Anand model stress multiplier
Ψ - Phase angle of fracture
v - Poisson’s ratio

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Microelectronic packages offer electrical connections, mechanical and environmental support, and thermal connections through lead-free solder interconnect. Ball grid array (BGA) packages with lead-free solder joints are widely utilized in the electronics industry due to their reliability with many levels of interconnects and enhanced connectivity with smaller thermal resistance. The interconnections could be pinned, formed conductors, terminals, or flip-chip solder bumps. Flip-chip bonding is the most favorable interconnections due to high density and reliable interconnection technology [1].

The flip-chip package emerged as an attractive solution for complicated and highly integrated systems with multiple functions such as mobile applications. It is keeping up with the times and evolving new innovative solutions to serve advanced technologies such as 2.5D and 3D. The flip-chip is used in the global light-emitting diode (LED), laptops, desktops, consumer applications, and automotive sector. The primary key players in the flip-chip market include Amkor Technology Inc., UTAC Holdings Ltd, Chipbond Technology Corporation, Intel Corporation, Taiwan Semiconductor Manufacturing Company Limited, TF AMD Microelectronics Sdn. Bhd, Global Foundaries U.S. Inc., Powertech Technology Inc., and TongFu Microelectronics Co.

Although emerging markets are driving to fine pitch copper (Cu) pillar bumps [2], conventional lead-free solder joints for BGA packages are still needed in packaging technology to meet customer’s demand [3, 4]. Towards the development of semiconductor and electronic packaging technology, flip-chip ball grid array (FCBGA) assembly has become necessary in the electronics industry due to the high interconnection density and lower cost [4, 5]. The new generation lead-free solders are designed for applications in a harsh environment. Therefore, they need to have excellent thermal and mechanical resistance under temperature cycling and long dwell conditions. In a real application, the solder joint is subjected to various types of loading such as thermal reflow [6, 7], thermal cycling [8-10], and impact [11-13] that caused thermal and mechanical stresses. Table 1.1 shows an example of the temperature operating environments for various electronics applications in different fields. For example, BGA packages are needed in vehicle engine control, braking, and communication in automotive applications.

Table 1.1 Examples of usage conditions in various fields [14]

Field	Temperature range	Cycles/year	Service time	Failure rate
Digital cameras	0 to 60 °C	365	1 year	1 %
Smart watch	15 to 60 °C	1460	5 years	0.1 %
Telecom	-40 to 85 °C	365	7 to 20 years	0.01 %
Aircraft	-55 to 95 °C	365	20 years	0.001 %
Automotive	-55 to 95 °C	100	10 years	0.1 %

Previous work has reported that lead-free solder joints are susceptible to brittle fracture nature due to the rate of intermetallic phase coarsening in the bulk solder under prolonged temperature and mechanical load cycles [15]. In the critically-stressed solder joint, failure occurs by progressive accumulation of damage throughout the temperature cycles. Final fracture is contributed by crack initiation and subsequent crack propagation processes. Besides, fast loading cycles are likely to introduce strain rate effects on the solder response and dictate the type of failure. The slow strain rate may deform the critical solder joint plastically, resulting in ductile failure across the bulk solder. In contrast, high strain rate loading may cause brittle fracture near the solder/intermetallic compound (solder/IMC) interface [16, 17].

Consequently, accurate reliability prediction of solder joints should acknowledge the progressive damage process under temperature and strain rate effects. Researchers need to study further the deformation behavior and damage process of lead-free solders over a wide range of temperature and strain rates, particularly at higher straining rates. Most of the open literature is investigated on the failure process mechanism in the brittle solder/IMC interface solder joints at room temperature conditions [18, 19].

Experiments such as board-level drop test (BLDT), solder shear push test, ball pull test, and impact test are frequently carried out to examine the mechanics behavior of BGA solder joints [15, 20-27]. In high-speed ball shear or pull test, the solders are sheared or pulled individually to examine the brittle force-displacement response of the solder joint. The testing parameters such as the geometry of the solder ball, aging duration and temperature, bulk solder composition, shearing speed, gripping pressure, and shear tool stand-off height should take into consideration while conducting the tests as the resulting force would be affected. There is some evidence that brittle materials had cracked near the IMC or along the IMC layer under high strain rate mechanical loading [25, 26]. Prediction of solder joint reliability under temperature cycling experiments and impact conditions is costly and time-consuming. Such conditions motivate the present study to employ a finite element analysis approach for predicting the failure process of lead-free solder interconnects.

The research work is an ongoing collaboration with Intel Technology, Penang, Malaysia.

1.2 Problem Statement

Lead-free tin-silver-copper (Sn-Ag-Cu) solder alloys in the BGA package experience a high temperature of solder reflow to melt the solder alloys. During solder reflow cooling, the solder joints experience a large variation in reflow cooling temperature caused by thermal mismatches between various materials in the package having dissimilar coefficients of thermal expansion. The solder joints are experiencing temperature excursion between -40 °C and 125 °C during reliability temperature cycles. As the solder joints are subject to heating and cooling rate during temperature cycles, the thermo-mechanical deformation response of the solder joints is dependent on temperature and strain rate conditions [28, 29]. Progressive damage in solder joints contributes to device failure. Then, the reliability of the solder joint becomes a significant concern in electronic industries since it is the weakest link in the typical BGA package. The transition from ductile failure to brittle failure occurs at the strain rate of 1 s^{-1} [30] and $10^{-2} – 10^{-1}$ s^{-1} [17] under tension loading. The solder/IMC interface fracture that occurs during temperature cycles needs to be examined. The available damage-based models, CZM for the solder/IMC interface and CDM for the bulk solder failure are limited to room temperature conditions [19, 31-33]. Thus, this study would extend the CZM parameter values as a function of temperature and strain rate effects for better prediction accuracy. The development of such a response is significant in this research. The effect of temperature and strain rate on the resulting deformation response and failure process is demonstrated for the typical BGA package with Sn-4.0Ag-0.5Cu solder joints.

1.3 Research Objectives

The study aims to establish a validated finite element (FE) damage-based predictive model for SAC405 solder joints, based on the reflow cooling process and the reliability temperature cycles. The specific research objectives are described as follows:

(a) To quantify temperature- and strain rate-dependent properties of the solder/IMC interface of SAC405 solders alloy through a combined experimental-FE approach.

(b) To establish the effects of temperature and strain rates on the resulting deformation response and failure process of the BGA solder joints.

(c) To validate the damage-based material model of the SAC405 solder/IMC interface on the sensitivity of temperature cycle parameters.

1.4 Scopes of the Study

The present study is focused on the determination of solder/IMC interface material properties for use in solder joints reliability prediction, and the research work is limited to the following aspects:

1. SAC405 solder joints with Cu_6Sn_5 intermetallic compound layer as a demonstrator solder material.

2. Conduct solder ball shear and pull tests of SAC405 solder joints on a BGA package using DAGE 4000 bond tester at displacement loading rates ranging from 100 µm/s to 600 µm/s to observe rate-dependent response of the solder joints.

3. FE simulations using Abaqus version 6.14 commercial software:

    (a) 3D single solder shear push test (SPT) under rate-dependent loading to determine the solder/IMC interface properties.

    (b) BGA test assembly subjected to reflow cooling and temperature load cycles incorporated with temperature- and rate-dependent damage-based models.

4. Combine experimental results and predicted FE simulation results of solder ball SPT to determine the CZM properties of the solder/IMC interface.

5. Evaluate the bulk solder failure using Rice-Tracey (R-T) damage model and CZM formulation to account for temperature-dependent solder/IMC interface fracture.

6. Evaluate the capability of the predicted damage-based models that depend on temperature and strain rate using BGA test assembly under reflow cooling process and reliability temperature cycles.

1.5 Significance of the Study

Lead-free solder joints in the BGA packages are widely used in electronic packaging production. The concern on the reliability of solder joints arises from the different thermal and mechanical loading exposed to the materials used in various electronic fields. A computational model that can predict the long-term reliability of the solder joints is indispensable for the newly-designed BGA packages. The damage mechanics-based predictive model developed in this thesis offers an accurate prediction of reliability by incorporating the temperature and strain-rate dependent parameters. This FE simulation framework shall contribute to the industry requirements in developing electronic packages at a low cost by reducing the number of experimental testing. This, in turn, shall push the microelectronics industries in meeting the requirements for low cost, high reliability, and faster time-to-market of new packages.

1.6 Thesis Layout

This thesis is divided into seven chapters. In Chapter 1, the background of the research and the needs of the study are introduced. The outstanding issue of lead-free solder interconnects reliability is described, and the proposed failure mechanism model points out. The objectives, scope of work, and significance of this research are also presented.

Chapter 2 reviews the current microelectronic reliability technology. The temperature and strain rate material properties of solder material, the formation of intermetallic layers during reflow soldering, the role of temperature and strain rate in the solder joints reliability, unified constitutive model and damage-based models, available mechanical testing for reliability assessment, and summary of previous FE simulation work on the mechanical behavior of lead-free solder joint is presented. An overview of the literature review is also provided.

Chapter 3 illustrates the flowchart of the research work. It includes the details of the experimental part and the FE simulation model. The experimental setup and FE model configuration of SAC405 solder joints are clarified. The details of FE simulation, such as geometry, material properties, loading, and boundary conditions are given. The fractographic analysis on the fractured surface after mechanical tests are presented.

Chapter 4 discusses the methodology for determining the CZM interface properties of SAC405 solder joints under the solder shear push test. The computational-experimental approach is employed to extract the interface properties accurately. The dependence of temperature on lead-free solder joints is quantified through load-displacement curves at different straining rates.

In Chapter 5, the reliability of the SAC405 solder joint due to reflow cool-down and temperature cycles loading is discussed. The deformation and damage processes at the bulk solder and solder/IMC interface are examined. The results in terms of evolution and distributions of von Mises stress, accumulated inelastic strain, and damage criteria are presented. The damage mechanics are examined by integrating the established temperature- and rate-dependent interface properties, as described in Chapter 4.

Chapter 6 discusses the mechanic behavior and damage process on the SAC405 bulk solder and the brittle solder/IMC interface fracture under temperature cycles ranging from -40 to 125 °C. Four temperature cycles load cases (TC1, TC2, TC3, and TC4) and one thermal shock (TR1) cycle are simulated in FEA simulation The results are presented in terms of the deformation of BGA test assembly, distribution and evolution characteristics of stresses and inelastic strain as well as the damage process.

Chapter 7 presents the conclusion and recommendation of this thesis. The main findings and conclusions are highlighted as well as the recommendations for future work.

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