

**FRACTURE CHARACTERIZATION AND
ANALYSIS OF LEAD-FREE SOLDER JOINTS**

VED PRAKASH SHARMA



DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2022

FRACTURE CHARACTERIZATION AND ANALYSIS OF LEAD-FREE SOLDER JOINTS

by

VED PRAKASH SHARMA

DEPARTMENT OF MECHANICAL ENGINEERING

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2022

Certificate

This is to certify that the thesis entitled “**Fracture Characterization and Analysis of Lead-Free Solder Joints**” submitted by **Ved Prakash Sharma (2015MEZ8492)** to the Indian Institute of Technology Delhi (India) in the Department of Mechanical Engineering is a bonafide research work carried out by him under my supervision. I consider it worthy of consideration for the award of the degree of **Doctor of Philosophy** of the Institute.

Dr. Naresh Varma Datla

Associate Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

New Delhi -110016, India

Declaration

I certify that

- a. The work contained in the Thesis is solely the result of my work.
- b. The work has been done under the guidance of my supervisor.
- c. The work has not been submitted for any other degree in any other institute.
- d. I have followed the guidelines provided by the institute in writing the Thesis.
- e. I have conformed to the norms and guidelines given in the ethical code of conduct of the Institute.
- f. Whenever I have quoted written materials from other sources, I have given due credit to the sources by citing them and giving the required details in the references.

(Ved Prakash Sharma)

Acknowledgments

First of all, I owe my deepest gratitude to my doctoral supervisor **Prof. Naresh Varma Datla** for providing me the opportunity to pursue a doctoral dissertation and for his continuous guidance and support in pursuit of my research. I feel fortunate and honored to have learned from his immense knowledge and plentiful experience that have encouraged me all the time in my academic research and daily life.

I would like to extend my sincere thanks to **Prof. J K Dutt**, **Prof. Rajesh Prasad**, and **Prof. D K Dubey** for their time, insightful comments, and suggestion as doctoral student research committee members.

I am grateful to the **Director, National Institute of Technology Srinagar**, and the **HOD, Mechanical Engineering Department, NIT Srinagar** for their continuous support. I also thank my colleagues at NIT Srinagar for their support and encouragement.

I thank my friends and lab mates for their help, stimulating discussions, and creating a cordial working environment. They made this long journey enjoyable.

Finally, my deep and sincere gratitude to my parents, Brahma Nand and Mira for their unparalleled love, help, and support. Special thanks to my brother, Satya Prakash Sharma for always being there for me both as a brother and a friend. I would like to dedicate this thesis to my family.

Abstract

A typical electronic device consists of mainly three parts namely integrated circuits, printed circuit board (PCB), and interconnections joining these two parts. The solder joints are commonly used for these interconnections which serve two purposes i.e., both as an electrical connection and a mechanical joint. The ball grid array (BGA) arrangement of interconnections is commonly used owing to its simple design. The increasing use of electronic devices in harsh environments such as the military, aerospace, and aviation make the solder joints subjected to various thermo-mechanical loads. As the size of these joints is relatively smaller (cross-section), it leads to higher stresses and thereby making them more prone to failure. So, the failure characterization of the solder joints needs to be done to improve the reliability of the joint.

A mix of experimental and finite element modeling based approaches was used to characterize the solder joint failure. The double cantilever beam (DCB) specimens were used to study the fracture behavior of these joints. The mode-I and mixed-mode fracture tests were done to study the effect of bond-line thickness and mode-mixity. The critical energy release rate for crack initiation of the joint (G_{ci}) was correlated to the fractography study and plastic zone area (PZA) just ahead of the pre-crack. The G_{ci} was obtained from fracture tests based on the beam on elastic foundation model. The mode-I G_{ci} increased with bond-line thickness in the range of 110 – 880 μm . This increase in G_{ci} was attributed to the increased PZA and ductility of the fracture with increasing bond-line thickness. The G_{ci} increased marginally with increasing mode-mixity in the range 0 – 33°. This marginal increase in G_{ci} was due to a marginal increase in PZA. The FE modeling was done to model the fracture in the solder joints based on cohesive zone model (CZM) following a bilinear traction separation law (TSL). The

maximum traction of the TSL increased with increasing bond-line thickness, however it remained the same with increasing mode-mixity.

The effect of time and temperature of the service environment on the joint strength was studied by aging studies and mode-I DCB fracture test. The DCB specimens were isothermally aged at 200 °C for 6 to 96 h before mode-I fracture tests. The G_{ci} of the joint was correlated with the intermetallic compound (IMC) layer thickness, fractography study, and fracture path. The G_{ci} of the joint reduced significantly with aging time. This decrease in G_{ci} was mainly attributed to an increase in IMC layer thickness and change in failure behavior from a ductile fracture in bulk solder (for the as-reflowed specimens) to brittle fracture about the IMC layer (for aged specimens). The loading rate (cross-head speed) effects on the joint were studied by correlating the G_{ci} of the joint to fractography study, fracture path, and the fraction of IMC fracture with increasing loading rate in the range of 0.1 to 500 mm/min. The G_{ci} of the joint first increased, and then decreased significantly with increasing loading rate. The fractography study suggested that the failure changed from ductile to a mix of ductile and brittle fracture with increasing loading rate.

Finally, the effect of Ag content on the failure behavior of the joint was studied by the mode-I DCB fracture tests. The G_{ci} of the joint was correlated to the fractography study, PZA just ahead of the pre-crack, and IMC layer thickness. Three different solder alloys namely, Sn-0.7Cu, Sn-0.3Ag-0.7Cu (SAC0307), and Sn-3.0Ag-0.5Cu (SAC305) were used to prepare DCB specimens. The G_{ci} of the joint was found to be in the increasing order for the solder joints SAC305, SAC0307, and Sn-0.7Cu. This trend was mainly attributed to significantly higher PZA, thinner IMC layer, and ductile failure for the Sn-0.7Cu solder joint. The failure changed to a combination of ductile and brittle fracture for the other two solder joints i.e., SAC0307 and SAC305.

In this work, the effects of factors such as bond-line thickness, mode-mixity of fracture, aging time, loading rate, and Ag content in the solder were studied on the fracture behavior of the solder joints using DCB specimens. The fracture toughness of the joint, and the ductility during fracture increased with increasing bond-line thickness in the studied range. Increasing the mode-mixity of fracture in the range $\psi = 0 - 33^\circ$, marginally increased the fracture toughness of the joint. The FE model using the TSL predicted the failure of the joint reasonably well. The fracture toughness of the joint decreased significantly and the failure changed from ductile to brittle with increasing aging time. Increasing the loading rate first increased the and then significantly decreased fracture toughness of the joint. The failure behavior also changed from ductile to a mix of ductile and brittle failure with the increasing loading rate. The Sn-0.7Cu/Cu solder joint had significantly higher fracture toughness than SAC0307/Cu and SAC305/Cu solder joints. Overall, it was observed that these factors have a significant effect on the reliability and failure behavior of the solder joint.

सार

एक सामान्य इलेक्ट्रॉनिक उपकरण में मुख्य रूप से तीन भाग होते हैं, एकीकृत सर्किट, मुद्रित सर्किट बोर्ड (पीसीबी), और इन दो भागों को जोड़ने वाले जोड़। सोल्डर जोड़ आमतौर पर जो दो उद्देश्यों की पूर्ति करते हैं, विद्युत कनेक्शन और यांत्रिक जोड़। बॉल ग्रिड ऐरे (बीजीए) जोड़ की व्यवस्था आमतौर पर इसके सरल डिजाइन के कारण उपयोग की जाती है। सैन्य, एयरोस्पेस और विमानन जैसे कठोर वातावरण में इलेक्ट्रॉनिक उपकरणों के बढ़ते उपयोग की वजह से सोल्डर जोड़ों पर विभिन्न प्रकार के थर्मो-मैकेनिकल भार लगते हैं। चूंकि इन जोड़ों का आकार अपेक्षाकृत छोटा होता है, यह उच्च तनाव की ओर ले जाता है और इस तरह उन्हें विफलता के लिए अधिक प्रवण बनाता है। इसलिए जोड़ की विश्वसनीयता में सुधार के लिए जोड़ों की विफलता लक्षण वर्णन करने की आवश्यकता है।

जोड़ों की विफलता को चिह्नित करने के लिए प्रयोगात्मक और परिमित तत्व मॉडलिंग आधारित दृष्टिकोणों के मिश्रण का उपयोग किया गया था। इन जोड़ों के फ्रैक्चर व्यवहार का अध्ययन करने के लिए डबल कैंटिलीवर बीम (डीसीबी) नमूनों का उपयोग किया गया था। बॉन्ड-लाइन मोटाई और मोड-मिश्रण के प्रभाव का अध्ययन करने के लिए मोड- I और मिश्रित-मोड फ्रैक्चर परीक्षण किए गए थे। दूरार दीक्षा (जीसीआई) के लिए नाजूक ऊर्जा रिलीज दर को फ्रैक्टोग्राफी अध्ययन और प्लास्टिक क्षेत्र (पीजेडए) से सहसंबद्ध किया गया था। जीसीआई को लोचदार नींव मॉडल पर बीम के आधार पर तथ्यात्मक परीक्षणों से प्राप्त किया गया था। मोड-I जीसीआई 110 - 880 माइक्रोन की सीमा में बॉन्ड-लाइन मोटाई के साथ बढ़ा। जीसीआई में इस वृद्धि को प्लास्टिक क्षेत्र में वृद्धि और बंधन-रेखा की मोटाई बढ़ने के साथ फ्रैक्चर की लचीलापन के लिए जिम्मेदार ठहराया गया था। जीसीआई 0 - 33 डिग्री की सीमा में मोड-मिश्रण बढ़ने के साथ मामूली रूप से बढ़ा। जीसीआई में यह मामूली वृद्धि पीजेडए में मामूली वृद्धि के कारण थी। द्विरेखीय ट्रैक्शन सेपरेशन लॉ (टीएसएल) का पालन करते हुए कोसिव जोन मॉडल (सीजेडएम) के आधार पर सोल्डर जोड़ों में फ्रैक्चर को मॉडल करने के लिए परिमित तत्व मॉडलिंग की गई थी। टीएसएल का अधिकतम कर्षण बॉन्ड-लाइन की मोटाई बढ़ने के साथ बढ़ा, हालांकि यह मोड-मिश्रण बढ़ने के साथ समान रहा।

जोड़ शक्ति पर सेवा वातावरण के समय और तापमान के प्रभाव का अध्ययन aging और मोड-I डीसीबी फ्रैक्चर परीक्षण द्वारा किया गया था। मोड- I फ्रैक्चर परीक्षण से पहले डीसीबी नमूने 200 डिग्री सेल्सियस पर 6 से 96 घंटे के लिए aging के थे। जोड़ का जीसीआई इंटरमेटेलिक कंपाउंड (आईएमसी) परत की मोटाई, फ्रैक्चरोग्राफी अध्ययन और फ्रैक्चर पथ के साथ सहसंबद्ध था। उम्र बढ़ने के समय के साथ संयुक्त का आईएमसी काफी कम हो गया। जीसीआई में यह कमी मुख्य रूप से आईएमसी परत की मोटाई में वृद्धि और थोक सोल्डर (सामान्य डीसीबी) में एक नमनीय फ्रैक्चर से आईएमसी परत (वृद्ध नमूनों के लिए) के भंगुर फ्रैक्चर से विफलता व्यवहार में परिवर्तन के लिए जिम्मेदार ठहराया गया था।

जोड़ पर लोडिंग दर (क्रॉस-हेड स्पीड) प्रभावों का अध्ययन जोड़ के जीसीआई को फ्रैक्चोग्राफी अध्ययन, फ्रैक्चर पथ, और आईएमसी फ्रैक्चर के अंश को 0.1 से 500 मिमी / मिनट की सीमा में बढ़ती लोडिंग दर के साथ सहसंबंधित करके किया गया था। संयुक्त की जीसीआई पहले बढ़ी, और फिर लोडिंग दर बढ़ने के साथ काफी कम हो गई। फ्रैक्चोग्राफी अध्ययन ने सुझाव दिया कि बढ़ती लोडिंग दर के साथ विफलता नमनीय से नमनीय और भंगुर फ्रैक्चर के मिश्रण में बदल गई।

अंत में, मोड- I डीसीबी फ्रैक्चर परीक्षणों द्वारा जोड़ के विफलता व्यवहार पर चांदी सामग्री के प्रभाव का अध्ययन किया गया। संयुक्त के जीसीआई को फ्रैक्चोग्राफी अध्ययन, पीजेडए पूर्व-दरार के ठीक आगे, और आईएमसी परत की मोटाई से सहसंबद्ध किया गया था। डीसीबी नमूने तैयार करने के लिए तीन अलग-अलग सोल्डर मिश्र, Sn-0.7Cu, Sn-0.3Ag-0.7Cu (SAC0307), और Sn-3.0Ag-0.5Cu (SAC305) का उपयोग किया गया था। जीसीआई SAC305, SAC0307, और Sn-0.7Cu के बढ़ते क्रम में पाया गया। इस प्रवृत्ति को मुख्य रूप से उच्च PZA, पतली आईएमसी परत, और Sn-0.7Cu जोड़ के लिए नमनीय विफलता के लिए जिम्मेदार ठहराया गया था। विफलता अन्य दो सोल्डर जोड़ों यानी SAC0307 और SAC305 के लिए नमनीय और भंगुर फ्रैक्चर के संयोजन में बदल गई।

इस काम में, डीसीबी नमूनों का उपयोग करके सोल्डर जोड़ों के फ्रैक्चर व्यवहार पर बॉन्ड-लाइन मोटाई, फ्रैक्चर के मोड-मिश्रण, aging समय, लोडिंग दर और सोल्डर में चांदी सामग्री जैसे कारकों के प्रभावों का अध्ययन किया गया। अध्ययन की गई सीमा में बॉन्ड-लाइन की मोटाई बढ़ने के साथ जोड़ की जीसीआई, और फ्रैक्चर के दौरान लचीलापन बढ़ गया। 0 - 33 ° की सीमा में फ्रैक्चर के मोड-मिश्रण को बढ़ाकर, जोड़ के फ्रैक्चर की कठोरता में मामूली वृद्धि हुई। टीएसएल का उपयोग करने वाले एफई मॉडल ने संयुक्त रूप से अच्छी तरह से विफलता की भविष्यवाणी की। aging समय के साथ जोड़ की जीसीआई काफी कम हो गई और विफलता नमनीय से भंगुर हो गई। लोडिंग दर में वृद्धि ने पहले जोड़ की फ्रैक्चर बेरहमी को बढ़ाया और फिर काफी कम कर दिया। बढ़ती लोडिंग दर के साथ विफलता व्यवहार भी नमनीय से नमनीय और भंगुर विफलता के मिश्रण में बदल गया। Sn-0.7Cu/Cu सोल्डर जोड़ में SAC0307/Cu और SAC305/Cu सोल्डर जोड़ों की तुलना में काफी अधिक जीसीआई थी। कुल मिलाकर, यह देखा गया कि इन कारकों का मिलाप संयुक्त की विश्वसनीयता और विफलता व्यवहार पर महत्वपूर्ण प्रभाव पड़ता है।

Table of Contents

Title Page	i
Certificate	iv
Declaration.....	v
Acknowledgments.....	vi
Abstract (English)	vii
Abstract (Hindi)	x
Table of Contents	xii
List of Figures	xiv
List of Tables	xviii
List of Abbreviations.....	xxi
Chapter 1 Introduction.....	1
1.1 Motivation	1
1.2 Solder alloys.....	2
1.3 Solder joint failure study approaches	4
1.3.1 Qualitative approach	6
1.3.2 Stress-based approach.....	8
1.3.3 Fracture mechanics approach.....	9
1.4 Fracture mechanics based studies on solder joints.....	12
1.4.1 Effect of joint geometry	12
1.4.2 Effect of solder composition.....	13
1.4.3 Effect of mode-mixity of fracture	13
1.4.4 Effect of IMC layer.....	13
1.4.5 Effect of strain rate of loading	14
1.5 Numerical modeling.....	15
1.6 Research gaps.....	18

1.7	Objectives.....	19
1.8	Methodology	20
1.9	Thesis Outline	20
Chapter 2 Study of Bond-line Thickness and Mode-mixity Effects		23
2.1	Introduction	23
2.2	Experimental procedure	25
2.2.1	Specimen preparation.....	25
2.2.2	Fracture tests	27
2.2.3	Calculation of G and ψ	29
2.3	Finite element modeling.....	31
2.3.1	Cohesive zone modeling	31
2.3.2	FE analysis for PZA ahead of the crack-tip	35
2.4	DCB fracture test results	36
2.4.1	Crack initiation at the tip of the joint in DCB fracture test.....	36
2.4.2	Effect of bond-line thickness	39
2.4.3	Effect of mode-mixity	43
2.5	Traction–separation law for modeling the crack initiation in the joint.....	45
2.5.1	Effect of bond-line thickness on TSL	45
2.5.2	Effect of mode-mixity on TSL.....	51
2.6	Conclusion.....	52
Chapter 3 Study of Aging time and Loading Rate Effects.....		53
3.1	Introduction	54
3.2	Experimental procedure	56
3.2.1	Specimen preparation and aging.....	56
3.2.2	Fracture tests and calculation of G	57
3.2.3	Fractography and IMC layer thickness measurement.....	58
3.3	Results and Discussion.....	60

3.4	Effect of aging time.....	60
3.4.1	G_{ci} of the joint	60
3.4.2	IMC layer thickness	63
3.4.3	Failure surface and EDS analysis	65
3.5	Effect of loading rate.....	70
3.5.1	G_{ci} of the joint	70
3.5.2	Failure surface and EDS analysis	72
3.6	Conclusion.....	76
Chapter 4 Fracture Behavior and Reliability of Ag Based Lead-free Solder Joints		77
4.1	Introduction	77
4.2	Experimental procedure	78
4.2.1	Specimen preparation.....	78
4.2.2	Fracture tests and calculation of G	79
4.2.3	Fractography and IMC layer thickness measurement.....	80
4.2.4	FE modeling for the plastic zone area (PZA) just ahead of the pre-crack tip....	80
4.3	Results and Discussion.....	82
4.3.1	Effect of Ag content in the solder alloy	82
4.3.2	PZA just ahead of the pre-crack.....	84
4.3.3	Fractography	86
4.3.4	IMC layer thickness	88
4.3.5	Discussion	89
4.4	Conclusion.....	90
Chapter 5 Conclusions and Future Work		91
5.1	Conclusions	91
5.1.1	Effect of bond-line thickness and mode-mixity of fracture	91
5.1.2	Effect of aging time and loading rate.....	92
5.1.3	Effect of Ag content.....	93

5.2	Future work	94
References		96
List of Publications.....		109
Bio-Data		110

List of Figures

Chapter 1

Fig. 1. 1 Schematic of a typical BGA package arrangement	2
Fig. 1. 2 Cracking in the solder joint in the bulk solder and at the solder-adherend interface ..	6
Fig. 1. 3 The three pure modes of fracture.....	10
Fig. 1. 4 Various traction separation laws (a) TSL based on Hillerborg model (b) bilinear TSL, (b) polynomial TSL, and (c) exponential TSL.....	16
Fig. 1. 5 Mode-I and mode-II dependent mixed-mode bilinear TSL.....	17
Fig. 1. 6 Flowchart of the methodology followed to characterize and predict the failure behavior of the solder joints.....	20

Chapter 2

Fig. 2. 1 DCB specimen with continuous solder joint having an initial crack length (a).	25
Fig. 2. 2 The DCB specimen along with the configuration of mixed-mode loading-jig for (a) $\psi = 33^\circ$, (b) $\psi = 20^\circ$, (c) $\psi = 0^\circ$. The camera setup used for optical measurement of the crack length is shown in (c), and (d) free body diagram of the links.	28
Fig. 2. 3 Flow chart for determining the TSL for the joint.	31
Fig. 2. 4 (a), (b) FE model of the DCB specimen with meshing and boundary condition for mode-I and mixed-mode loading ($\psi = 20^\circ$), respectively (c) enlarged image at the pre-crack tip with a cohesive layer for CZM and (d) enlarged image at the pre-crack tip without cohesive layer for PZA determination.	34
Fig. 2. 5 (a) The experimental load-displacement response and P_{cr} of the joint with 440 μm bond-line thickness tested under mode-I loading, (b) P_{cr} for the joint as observed by the onset	

of non-linearity and visual inspection method (c) P_{cr} for the joint as observed by the onset of non-linearity method for three different mode-mixities.	38
Fig. 2. 6 (a) The variation in G_{ci} with the bond-line thickness (b) effect of bond-line thickness on PZA at the onset of crack-initiation.	39
Fig. 2. 7 FE results showing the PZA ahead of the pre-crack tip at the onset of crack-initiation for the bond-line thickness of 440 μm ; $G = 803 \text{ J/m}^2$, $\text{PZA} = 5.4 \text{ mm}^2$	40
Fig. 2. 8 Failure surfaces of the tested DCB specimens fractured in mode-I loading with the different bond-line thicknesses (a) 110, (b) 440, and (c) 880 μm	42
Fig. 2. 9 SEM images of the failure surface taken at 500X (a) 110, (b) 440, and (c) 880 μm	43
Fig. 2. 10 Effect of mode-mixity on (a) G_{ci} , (b) PZA just ahead of the pre-crack tip at the onset of crack-initiation.	43
Fig. 2. 11 Observation of the FE based parametric study (a) effect of penalty stiffness and, (b) effect of traction on the predicted load-displacement response for DCB specimen with 440 μm solder joint thickness.	46
Fig. 2. 12 (a) Comparison of experimental and predicted load-displacement response for different bond-line thickness, (b) variation of bilinear TSL with the bond-line thickness (the continuous and dotted lines represent experimental and predicted responses, respectively), (c) FE results at the onset of crack-initiation for different bond-line thicknesses showing the variation of induced normal stress (S_{22}) with distance, just ahead of pre-crack tip, and (d) variation in mean, equivalent von Mises stress and triaxiality factor at the crack tip with bond line thickness.	49
Fig. 2. 13 (a) Comparison of experimental and predicted load-displacement response for different mode-mixities (the continuous and dotted lines represent experimental and predicted responses, respectively) (b) variation in bilinear TSL with the mode-mixity.	52

Chapter 3

Fig. 3. 1 Aging of the DCB specimen at 200 °C.	56
Fig. 3. 2 Images of the samples for (a) SEM and EDS analysis (b) IMC layer thickness measurement.	59
Fig. 3. 3 Effect of aging time on (a) the load-displacement response from the DCB fracture test (pre-crack length a in mm and aging time in h), (b) the G_{ci} and IMC layer thickness, and (c) parabolic variation in the IMC thickness with aging time.	62
Fig. 3. 4 Images from optical microscope showing the IMC layer thickness of DCB samples aged at 200 °C for (a) 0 h (as-reflowed), (b) 6 h, (c) 24 h, (d) 48 h, and (e) 96 h.	64
Fig. 3. 5 Failure surface images, SEM images, and EDS results for the region near the pre-crack of the fractured DCB samples aged for (a, b) 0, and (c, d) 6 h.	66
Fig. 3. 6 Failure surface images, SEM images, and EDS results for the region near the pre-crack of the fractured DCB samples aged for (a, b) 24, (c, d) 48, and (e, f) 96 h.	68
Fig. 3. 7 Variation in elemental composition on the fracture surface with aging time at different locations L1 – L8.	69
Fig. 3. 8 Effect of loading rate on (a) the load-displacement response from the DCB fracture test (pre-crack length a in mm and loading rate in mm/min) and (b) G_{ci} of the joint.	70
Fig. 3. 9 Failure surface image, SEM images, and area mapped EDS analysis results for the region near the pre-crack of the fractured DCB samples tested at (a) 0.1, (b) 1.0, (c) 40, (d) 100, and (e) 500 mm/min.	74
Fig. 3. 10 Variation in elemental composition on the fracture surface with loading rate.	75

Chapter 4

Fig. 4. 1 FE model of the DCB specimen along with meshing and boundary condition. An enlarged image at the pre-crack is shown for clarity.	81
Fig. 4. 2 Effect of Ag content on (a) load-displacement response, (b) G_{ci} , IMC layer thickness, and PZA.	82
Fig. 4. 3 Effect of Ag content on plastic zone just ahead of the pre-crack at the onset of crack-initiation for (a) Sn-0.7Cu (b) SAC0307, and (c) SAC305 solder joints.....	85
Fig. 4. 4 Effect of Ag content on the failure surface for (a) Sn-0.7Cu, (b) SAC0307, and (d) SAC305 solder joints.	88
Fig. 4. 5 Effect of Ag content on the IMC layer thickness for (a) Sn-0.7Cu, (b) SAC0307, and (d) SAC305 solder joints	89

List of Tables

Chapter 2

Table 2. 1 Material properties of adherend, solder layer [102] and links	35
Table 2. 2 Variation in G_{ci} of the joint, PZA, and PZS with bond-line thickness and mode-mixity:	44
Table 2. 3 Variation of TSL with bond-line thickness and mode-mixity:	47
Table 2. 4 Comparison of experimental and predicted P_{max} for different bond-line thickness and mode-mixity:	47

Chapter 3

Table 3. 1 Aging condition used in the literature:	57
Table 3. 2 Material properties of adherend and solder layer [102]:	58
Table 3. 3 Effect of aging time on G_{ci} of the joint and average thickness of IMC layer:	62
Table 3. 4 Variation in G_{ci} of the joint with loading rate:	72

Chapter 4

Table 4. 1 The mechanical properties of solder and Cu alloy:	80
Table 4. 2 Variation of G_{ci} , P_{max} , PZA, and average IMC layer thickness with Ag content in the solder:	83

List of Abbreviations

BGA	Ball Grid Array
SAC	Sn-Ag-Cu
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive spectroscopy
FE	Finite element
IMC	Intermetallic Compound
DCB	Double Cantilever Beam
PZA	Plastic zone area
CZM	Cohesive Zone modeling
TSL	Traction Separation Law