ANALYSIS OF SOLDER JOINT WITH COPPER PAD UBM IN ELECTRONIC PACKAGES - A FRACTURE MECHANICS APPROACH

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ABSTRACT

Solder joints in flip chip packages are soft and hence often prone to failure. The aim of this work is to estimate the fatigue life of solder joints. Initially the package is subjected to thermal cycling range of -40°C to 125°C. Results from analysis reveal that the edge solder is prone to large thermo-mechanical stresses/strains and hence is badly affected. The edge solder joint with the intermetallic compounds and the under bump metallization is modeled and subjected to fracture analysis using LEFM approach (crack assumed at solder-IMC interface). Two materials are taken for analysis. Sn-3.5Ag solder is highly reliable than Pb-5Sn material. Also the effect of IMC thickness on the fatigue life of the solder is studied. It is preferable to allow thin IMC formation during soldering process for longer solder life.

Key words: Solder joints, Linear Elastic Fracture Mechanics, Stress Intensity Factor.

1. Introduction

The electronic packaging trend is moving towards further miniaturization. Flip chip interconnection technology provides a solution to increasing demands on mimiaturization and weight reduction of portable electronic products. The product enables the direct chip attachment of silicon chips to substrates which is termed as flip-chip on board (FCOB) assembly where the chip is directly connected to the printed circuit board (PCB) by solder joints. The space between the chip and the board is encapsulated by an underfill epoxy resin to enhance reliability and performance. Many failure modes in flip chip packages such as delamination between die and underfill, brittle fracture of die and thermal fatigue of solder joints have been reported. This paper deals with thermal fatigue and fracture failure modes in solder joints. Figure 1 illustrates a solder bumped flip chip on PCB with underfill encapsulation. The components of the package are made of different materials and hence have different coefficients of thermal and moisture expansions. Frequent usage of package (powering ON and OFF conditions) and mismatching of CTEs and CMEs of various materials, cause the components to expand/contract at different rates. This induces large stress and strain (thermal & hygro) in the solder joints. This strain accumulated over a period of time, causes the solder joints to fail. This causes malfunctioning of the package, as an effect of which the electronic devices yield wrong results. Typically low temperature soft solders (MP below 260º) are employed to provide strong and highly reliable interconnections without damaging the substrate and other components during their normal working. Therefore a two dimensional plane strain section of the solder joint is taken for analysis. The severity of crack growth in solder joint is studied in this paper by evaluating its life under thermal backgrounds.

1.1 Theory of inter-metallic compounds

Silicon chip is connected to the PCB through soldering process. Two brittle inter-metallic compounds are formed between UBM pad and the solder material.

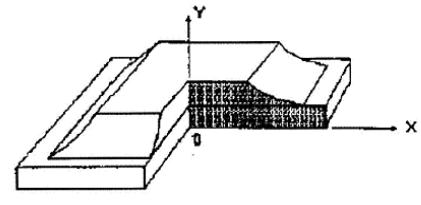

Fig.1 Solder-bumped flip chip on board

Between solder and the copper pad, IMC Cu_3Sn (ε-phase) is formed near copper pad and Cu_6Sn_5 (η-phase)is formed between copper pad and Cu_3Sn. They are highly hard and brittle. The total IMC thickness is

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distributed as 30% of Cu_3Sn and 70% of Cu_6Sn_5 [9]. It has been found from experimental analysis that fabricated specimens produced IMCs of thicknesses of 2.5, 2.64, 6.63 and 7.52 μm. [9]. Fracture behavior depends on the strength of solder, i.e., higher the strength, lower the energy for crack path. The growth of IMC layer is governed by a parabolic curve

$$w = w_0 + K \sqrt{t} \quad (1)$$

where

w is the thickness of IMC layer at any instant
w_0 is the initial IMC thickness
K is the growth rate of IMC
t is the time instant

The choice of methodology of analysing the fracture is difficult and depends on the material system. The fracture of any system can be analysed and its potency can be calculated by several approaches such as critical stress, crack opening displacement and J integral methods.

1.2 Fatigue life approach model for solder joint

The life cycle of a solder interconnection is proposed by Coffin & Mansion and Paris & Erdogan.

1.2.1 Paris empirical relation

The crack growth curve is divided into three regions such as threshold region, linear region and steep gradient region. The SIF in the threshold region takes a threshold value, below which the crack propagation does not occur. During the steep gradient region, the plastic zone dimension is larger compared to that of the specimen, due to which the SIF approaches the fracture toughness value and this leads to rapid crack extension.
During the middle linear region, the fatigue crack growth is represented by a linear relationship which is described by

$$da/dN = C (\Delta K)^m \quad (2)$$

where C and m are material constants, ΔK is the stress intensity factor range and N is the number of fatigue cycles to failure[8]. This equality is known as Paris law.

2. Modeling and Analysis of FCOB

2.1 Two dimensional plane strain FEA model of flip chip package

The finite element is based on a two-dimensional section of the FCOB package as illustrated by the shaded area in Figure 1. The package is modeled as per the dimension of the section shown in Figure 2(a) [9].

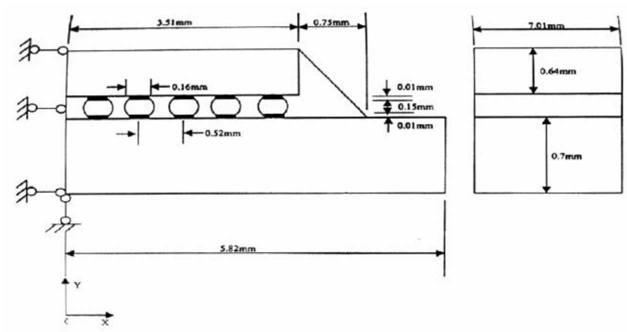

Fig.2(a) Geometry of FCOB

2.2 Thermal analysis of FCOB

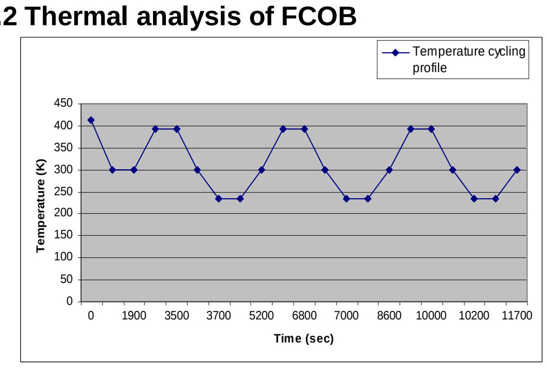

Fig. 2(b) Temperature cycling profile

To examine the solder joint on the basis of fracture criterion, the package has to be thermally analysed. Initially, the flip chip assembly is subjected to temperature cycling range of -40°C to 125°C as shown in Figure 2(b). The elastic and thermal properties in Table 1 are used for silicon chip, solder, encapsulant and the substrate in the model.[1,9]

Table 1:Material properties of FCOB package

Material	E (GPa)	CTE (ppm/C)	ν
Silicon	140	2.8	0.23
Epoxy	12.52	38	0.33
Sn-3.5Ag solder	62.08	21	0.32
Pb-5Sn solder	19	-	0.4
FR-4	22.4	20	0.14

The finite element mesh is shown in Figure 2(c).The stress distribution emanated from the analysis is more concentrated at the edge solder joint, resulting in its immediate failure. On these grounds, the edge solder has to be further analysed to estimate its fatigue life.

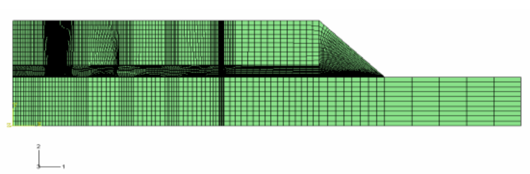

Fig.2(c) Mesh model of FCOB

3. Modeling and Analysis of Solder Joint

3.1 Two dimensional plane strain FEA model of Sn-3.5Ag solder joint

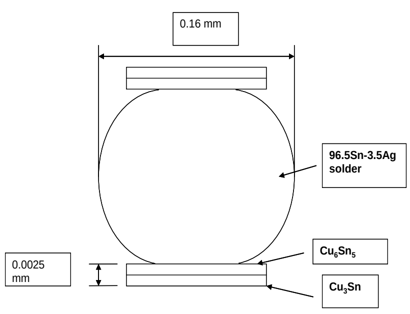

Fig. 3(a) Geometry of solder

The dimension of the solder joint is shown in Figure 3(a).The diameter of solder joint is 0.16 mm and the IMC thickness is taken as 2.5 μm. The UBM pad is 0.01 mm thick [9]. The Cu_6Sn_5 comprises of 70% of total IMC thickness.

Table 2:Material properties of solder assembly

Material	E (GPa)	ν	K_{IC} (MPa√m)
Sn-3.5Ag solder	62.08	0.32	4.7
Pb-5Sn solder	19	0.4	-
Copper pad	117	0.3	-
Cu_6Sn_5	85.56	0.309	1.4
Cu_3Sn	108.3	0.299	1.7

The solder joint is modeled with UBM pad and inter-metallic compounds. The elastic properties in Table 2 are used for solder, copper pads and the IMCs in the model [1, 2 and 9].

3.2 Fracture Analysis of solder joint

Equivalent thermo- mechanical loads of 1.54N, 1.57N, 0.85N at temperatures of -40°C, 23°C, and 125°C respectively are used to conduct fracture analysis [3]. These loads are converted into pressure loading, applied to the two edges of the solder joint, which represents the actual loading behavior in a FCOB package.
Crack generally is initiated at the solder–IMC (Cu_6Sn_5) interface [4]. Linear Elastic Fracture Mechanics (LEFM) approach is adopted for the analysis. An initial crack size is assumed at the solder-IMC interface. The stress intensity factor (SIF) is obtained at the crack tip, for different flaw sizes of 0.002 mm to 0.014 mm, under various loading conditions using ABAQUS software. The finite element mesh of solder bump assembly is shown in Figure 3(b).

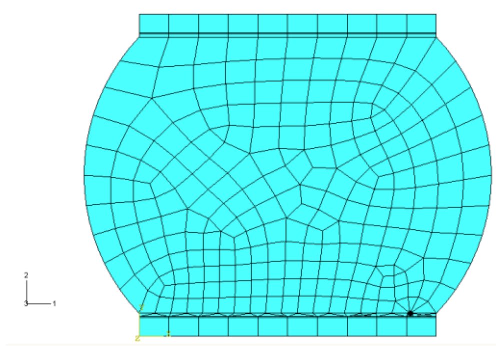

Fig. 3(b) Finite element mesh of solder bump

Material research is a wide field, opting for a better source, reliable, economical, non-hazardous and environment-friendly. In this study, two solder materials such as Sn-3.5Ag, Pb-5Sn with copper metal pads that may suit the condition against fatigue crack growth are tested to predict the solder fatigue life in the package.

The Paris law constants used for the calculation of fatigue life for different solder materials and their corresponding intermetallic compounds are listed in the Table 3. [5, 6]

Table 3: Paris law constants

Materials	Paris law coefficient,C	Paris law exponent, m
Sn-3.5Ag solder alloy	2.6 E-13	2.1
Pb-5Sn solder alloy	1.1 E-11	1.45
Cu_6Sn_5 IMC	3.16 E-12	3.1

4. Observations

4.1 Solder joint assembly

The solder joint assembly with the IMC and UBM is modeled with the crack at the solder-IMC interface. Each solder assembly is modeled with one independent crack length. The different crack lengths used are 0.002 to 0.014 mm (i.e., 1/80th to 1/12th of the total length of the solder). Therefore the analysis was conducted in seven models of different crack lengths i.e., the crack propagates initially from a length of 0.002 mm to a final length of 0.014 mm which is visualized through these seven models. The failure (unstable crack propagation) was assumed to start only after 1/12th of the total length of the solder joint**.**

4.2 Sn-3.5Ag with copper UBM

The variation of SIF values with crack size for Sn-3.5Ag solder with copper UBM pad is shown in Figure 4(a)

It is observed that the stress intensity value increases with the crack size and load.

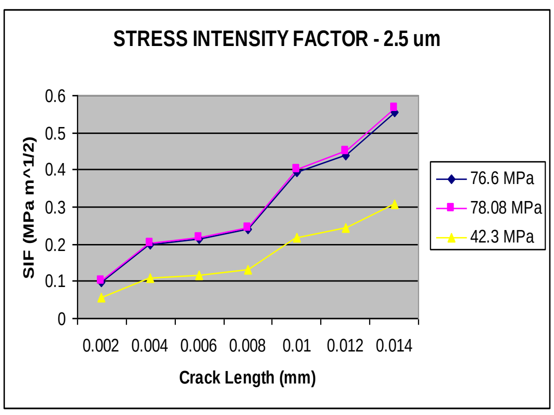

Fig.4(a) Relation between crack size and SIF

Fatigue life of Sn-3.5Ag solder assembly is found to be 303 million fatigue cycles, just to initiate the failure of the solder joint. Sn-3.5Ag solder material shows a better fatigue life compared to Pb-5Sn material. This is shown in Figure 4(b). Also fracture analysis is carried out for different IMC thicknesses of 2.64, 6.63, 7.52 µm. It is observed that fatigue life decreases with increase in IMC thickness. This is illustrated inFig 4 (b). Also the effect of elastic modulus (property) of the

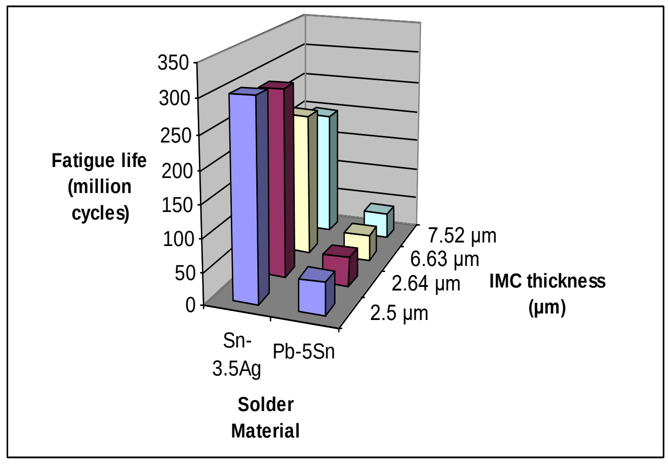

Fig. 4(b) Effect of IMC thickness on solder fatigue life

intermetallic compound, Cu_6Sn_5 on the solder fatigue life, for various Young's modulii of 85.56, 102, 134 GPa [7] is studied. This work reveals that fatigue life of solder decreases with increase in the value of Young's modulus. This is shown in Figure 4 (c).

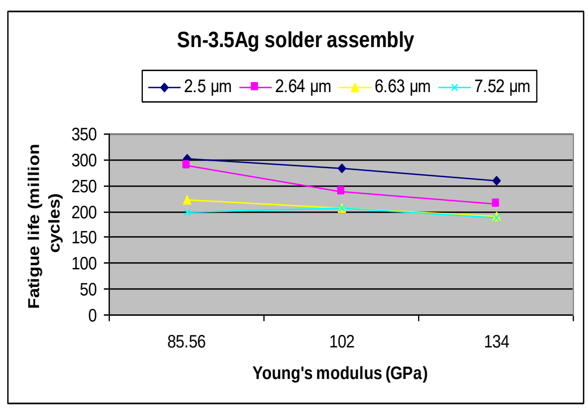

Fig.4(c) Effect of Young's modulus of IMC on solder fatigue life

4.3 Pb-5Sn with copper UBM

The lead-tin solder assembly with copper UBM and its IMCs was modeled and subjected to fracture analysis. Also the effect of property of the brittle IMC Cu_6Sn_5 i.e., the Young's modulus, on the fatigue life of the solder joint was evaluated and is shown in Fig. 4(d).

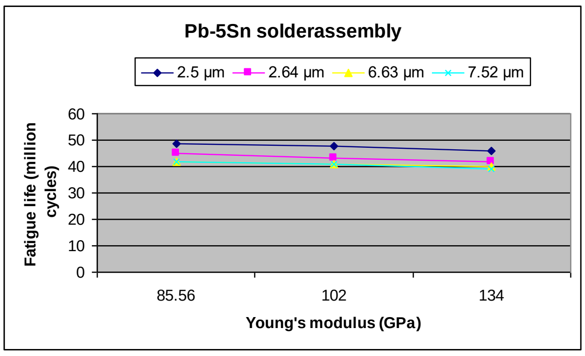

Fig.4(d) Effect of Young's modulus of IMC on solder fatigue life

5. Conclusions

Failure in a flip chip package occurs in the edge solder bump close to the boundary of the package because solder is soft compared to other material components of the package.

The tin-silver solder material with copper UBM which has good strength and creep resistance is highly reliable (303 million cycles for 2.5 µm IMC thickness) than the lead-tin solder assembly (49 million fatigue cycles). Due to carcinogenic nature of lead alloys and short life, its use can be avoided in Electronic packaging.

Solder fatigue life decreases by 35% with increase in IMC thickness by approximately three times. Also increase in Young's modulus of the Cu_6Sn_5 IMC decreases the solder fatigue life. Hence it is preferable to allow thin IMC formation, during soldering process, for longer solder lives. The formation of thick IMC can be prevented by allowing short reflow time and low reflow temperature.

6. References

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7. Nomenclature

Symbol	Meaning	Unit
a	Crack size	mm
N	Fatigue life	cycles
K_1	Stress intensity factor	MPa√m
K_{IC}	Fracture toughness	MPa√m
E	Young's modulus	GPa
α	Coefficient of thermal	ppm/°C
C	Paris law coefficient	Dimensionless
m	Paris law exponent	Dimensionless
ν	Poisson's ratio	Dimensionless

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