Aging Studies of PBGA Solder Joints Reflowed at Different Conveyor Speeds

S. H. Fan, Y. C. Chan, C. W. Tang, and J. K. L. Lai

Abstract—In this paper, the shear cycle fatigue properties of plastic ball grid array (PBGA) assemblies’ solder joints reflowed with three different profiles, and aged at 125 °C for four, nine, 16, 25, and 36 days are studied. The profiles were devised to have the same “heating factor,” which was defined as the integral of the measured temperature above the liquidus (183 °C) with respect to dwell time in the reflow profile, but to have different conveyor speeds. The effects of conveyor speed on the solder joint (nonaged and aged) fatigue lifetimes were investigated. It was found that with increasing the conveyor speed the solder joint shear fatigue lifetime could be improved substantially. Also, the shear fatigue lifetimes of aged solder joints decreased with increasing aging time and variation in fatigue lifetimes increased for faster conveyor speed. SEM and optical micrographs show that faster cooling rate caused a rougher interface of solder/IMC and less crystallization microstructure in solder joints. Rougher interface solder joints have a longer nonaged fatigue life. The thickness of IMC increases with increasing aging time and the growth rate for solder with faster cooling rate was larger. SEM cross section views reveal that cracks initiated at the acute position near the solder pad, then propagated along the interface of the bulk solder/IMC layer. Thicker IMC layers deteriorated fatigue life, so the fatigue lifetime variation of aged solder joints with fast cooling rate was larger.

Index Terms—Cooling rate, Cu–Sn intermetallics, intermetallic compound growth, plastic BGA, reliability, shear cycle fatigue life, solder joint.

I. INTRODUCTION

R ECENT advances in semiconductor devices have produced small feature sizes, increasing gate count and chip I/O. This trend has put increased emphasis on microelectronic packaging. Ball grid array (BGA) has become the package of choice.

The interconnection between BGA and printed circuit board (PCB) is through solder joints alone, i.e., BGA solder joints work as both electrical I/O and mechanical support. The fatigue properties of solder joints are critical to the reliability of BGA packages. On the other hand, due to the standoff height is much smaller than that of other surface mount technology (SMT) packages, such as quad flat package (QFP), and column grid array (CGA), BGA packages are more prone to solder joint fatigue problems than other SMT packages.

Cu–Sn intermetallic compound (IMC) forms instantaneously when Sn–Pb solder melts on the Cu pads. A thick Cu–Sn IMC layer may not only be created by the long reflow time and high reflow temperature during soldering, but also by prolonged storage and long term operation of the electronic assembly even at room temperature [1], [2]. Because of its brittle nature and microstructural mismatch with Sn–Pb solder and copper, that is too thick an IMC layer causes the interface in the solder joint to be more sensitive to stress [3], [4]. The effect is much more severe in small dimension BGA solder joints.

This paper investigates the effect of solder alloy microstructure on the kinetics of IMC growth in eutectic solder/copper solder joints formed by different cooling rate. The thickness growth of IMC layer is examined as function of aging time. The variation of solder joint fatigue lifetime with aging time was also investigated. Our research result may contribute to better understanding of diffusion behavior and microstructural evolution of IMC at the eutectic solder/copper substrate interface, so as to optimize the reflow parameters.

II. EXPERIMENTAL PROCEDURE

A. Sample Details

The 169-pin (solder ball) PBGA components have a peripheral dimension of 23 mm² and its (Bismaleimide triazine) BT substrate thickness is 0.5 mm. The 63Sn/37Pb solder ball has a nominal volume of 0.23 mm³. The solder pad pitch is 1.5 mm. The PCB size is 50 mm × 90 mm, with a thickness of 1.6 mm. The diameter of copper pad on PBGA and PCB side is 0.889 mm and 0.635 mm, respectively. After reflow, the solder joint has a maximum diameter of 0.800 mm in the middle part with the standoff height of 0.580 mm.

B. Soldering Process

A micro-placer machine was used to mount the BGA’s on PCB by using no-clean flux. After mounting, the testing boards were reflowed in a five-zone oven in compressed air atmosphere. The time-resolved temperature profiles near the solder joint and in the oven chamber air were recorded simultaneously by a wireless profiler. Fig. 1 shows the typical temperature profile. The PCB and BGA metallizations joined in daisy chains were used to perform electrical continuity test. X-ray microscopy was used to inspect for solder bridge and other anomalies.

C. Reflow Parameters

According to the general Newton Law of Cooling for convection heat transfer, for a particular time interval \( \Delta t(t_1-t_2) \), the system average heat exchange (heating or cooling) rate can
be expressed as

$$q = \frac{H}{\Delta t} = \frac{\int A \cdot h_m(T_s(t) - T_\infty(t))dt}{\Delta t} \quad (1)$$

where

- $H$ = system’s total heat exchange between a body and the surrounding free fluid from time $t_1$ to $t_2$;
- $A$ = total heat exchange area;
- $h_m$ = mean coefficient of heat transfer;
- $T_s$ and $T_\infty$ = surface temperature of the object and the temperature of the free fluid, respectively.

Fig. 1 is the typical reflow profiles for the PBGA’s. The 183°C melting temperature of the eutectic solder is defined as the reference temperature line—the liquidus. In our previous work [5], it was found that the integral of the measured temperature $T_s(t)$ above the liquidus line with respect to time, defined as “heating factor”, can characterize the reflow profile in the melting section.

In this work, the profiles were devised to have the same “heating factor,” but with different conveyor speeds; 10, 30, 50 in/min for profile #1, #2, and #3, respectively. Our previous work [6] showed that, by varying the conveyor speed, solder joint cooling rate was changed greatly.

D. Shear Cycling

An INSTRON MINI 44 tensile test machine was used to test the solder joint shear cycling life. The experimental setup is schematically shown in Fig. 2. In order to reduce the strain on the epoxy-glass substrate when the specimen was cyclically strained, the distance between the steel crosshead and the grip anvil was set to a small value and kept constant among the different test specimens. The test specimen (coupon) was cut carefully from 169-pin assembly in such a way that one specimen contains three columns (3 $\times$ 13) of solder balls (see Fig. 2). The tests were performed at room temperature and 60% relative humidity. The solder joints were cyclically sheared to constant displacement amplitude (0.18 mm). The shear load change with time and the peak loading of each shear cycle were recorded. The cycle, which the peak loading drops to 50% of that of the initial cycle, is defined as the fatigue life. The frequency of the tests was 0.43 Hz. The sample size was 15 for each kind of test.

The frequency of isothermal shear cycling test is generally in the rage of $10^{-4}$–1 Hz [7]. In this work, the choice of high frequency (0.43 Hz) is based on the following considerations:

1) shorting the testing time [7];
2) this work mainly investigated the influence of IMC layer on the solder joint failure lifetime.

IMC is more brittle than solder and Cu pad, under high frequency, cracks tend to occur near the IMC layer.

E. Fatigue Life Distribution

In this paper, the lifetime distribution of solder joints is modeled by the two-parameter Weibull cumulative distribution function, which has the following form [8], [9]:

$$F(x) = 1 - e^{(-x/\theta)^\beta} \quad (2)$$

In (2)

- $x$ = value of the random variable (number of cycles to failure, $N$, in the present study);
- $\beta$ = shape parameter (Weibull slope);
- $\theta$ = scale parameter (characteristic value).

The “best fit” Weibull parameters (for the median rank) $\beta$ and $\theta$ can be obtained by using the principles of least squares and ranking. The $x$ value corresponding to $F(x) = 0.5$ is called the number of cycles to failure at 50% failure rate ($N_{50\%}$). In this
study, the fatigue lifetime of solder joints is characterized using the parameter $N_{50\%}$.

III. RESULTS AND DISCUSSION

A. Microstructure Morphology

Fig. 3(a)–(c) are SEM cross section micrographs of solder/Cu pad of as-solidified solder joints reflowed by profiles #1, #2, and #3. The globular, single layer structure of $\eta$-phase Cu$_3$Sn$_5$ IMC was found in as-solidified solder joints. Duplex structure, with $\eta$-phase Cu$_3$Sn$_5$ next to the solder and $\varepsilon$-phase Cu$_2$Sn at the $\eta$-phase/copper interface of IMC layer was observed in aged solder joints. The mean thickness of the IMC layer growth in solder joints aged for a series of times were measured with the aid of a powerful image processing system, OPTIMAS, used in conjunction with a Nikon optical microscope. Since the magnification of optical microscopy is limited, the thickness of the $\varepsilon$-phase IMC layer, smaller than 1 $\mu$m, cannot be resolved independently with acceptable accuracy; therefore, the mean total thickness of the IMC layer was measured. Fig. 4 shows the measured result. The IMC thickness increases linearly with the square root of aging time. The result illustrates that the cooling rate of solder joints influences the growth rate of IMC layer. The thickness growth of IMC of the solder joints formed by profile #3 increases from 1.15 $\mu$m (four-day aging) to 3.55 $\mu$m (36-day aging), while the IMC thickness growth of the solder joints formed by profile #1 increases from 0.97 $\mu$m to 2.83 $\mu$m.

Fig. 5(a)–(c) show the optical views ($\times 400$) of solder alloy reflowed by profiles #1, #2, and #3. The dark and light colored areas are the Pb-rich and Sn-rich phases, respectively. The microstructure of slowly cooled solder [Fig. 5(a)] has the character of lamella/colony morphology. The Sn- and Pb-rich are arranged side by side in long range, differently oriented arrays that form colonies. The colony feature is still obvious in the smaller magnification ($\times 200$) view given by Fig. 6. As cooling rate increases, the colony size becomes smaller and the lamella becomes shorter [Fig. 5(b)]. In Fig. 5(c) (profile #3), the lamellae are hardly observable, and the colonies cannot be distinguished. Most areas have been replaced with the equiaxed Pb-rich phase embedded in the Sn-rich matrix.

B. Shear Fatigue Test Result

Solder joints manufactured by different profiles and aged for various days were subject to shear cycling test. Fig. 7 illustrates the test results ($N_{50\%}$). The lifetime decreases as the IMC layer thickens and the variation of faster cooled solder joints is larger.

C. Failure Mechanisms

Fig. 8 is the SEM cross section image of initial crack in a solder joint caused by shear cycling test. Fig. 9 is the SEM cross section view of a fully developed crack in a failed solder joint. It can be seen that crack initiated at acute position near solder pad, then propagated along the interface of the solder/$\eta$-phase IMC layer.

D. Discussion

For better understanding the mechanism of IMC growth in the Sn–Pb solder/copper pad system, several aspects should be noted: First, whether Cu or Sn is the dominant diffusing species?
As a general rule for binary diffusion couples, the element with the lower melting point has the larger diffusion constant. Therefore, for Cu–Sn system, tin should diffuse faster. Experiments reported in the literature [10] show that Cu₃Sn and Cu₅Sn₃ intermetallics form in the copper substrate below any diffusion barrier layers (Sn, Ni, Co, Cu₃Sn₂, etc.) added between the copper and tin. This suggests that tin diffuse into copper much more rapidly than copper diffuse into tin. Secondly, which rate-limiting factor, the diffusion-controlled growth or the interfacial reaction-controlled growth, is the main rate-limiting factor for IMC growth? The results of previous researches [1], [2], [11] as well as in this work demonstrate that the thickness of IMC layer is proportional to the square root of aging time, thus the growth is a diffusion-controlled process. So the growth of IMC can be described as [12]

\[ d = \sqrt{Dt} \]  

where

\[ d \] layer thickness;
\[ D \] diffusion coefficient;
\[ t \] aging time.

The diffusion coefficient is given by the Arrhenius equation

\[ D = D_0 \exp\left(-\frac{Q}{kT}\right) \]  

where

\[ D_0 \] diffusion constant;
\[ Q \] diffusion activation energy for the growth of IMC layer;
\[ k \] Boltzmann constant;
\[ T \] absolute temperature.

The third concern should be focused on the factors affecting the tin diffusion progress (or the diffusion activation energy \( Q \)). At the beginning of IMC growth, tin is available in the adjacent solder region next to the IMC/solder interface. However, along with the aging, the amount of tin available in that region will reduce, so tin diffuses from the inner solder region to the interface region. The microstructure and composition of the solder matrix should have an influence on the diffusion process. Previous research [11], [13] has shown that, after adding particles of Cu, Cu₃Sn, Cu₅Sn₃, Ag, Au, and Ni in eutectic solder alloy, the activation energy for the growth of IMC changes dramatically.

The theory on solidification of the eutectic phase [14] states that there are preferred crystallographic interfacial relations between the eutectic phases. A slowly cooled eutectic colony, to a first approximation, is two interpenetrating “single crystals,” one of each phase, oriented with respect to each other. In Fig. 5(a), the Pb-rich array are not perfect, in place a long narrow phase breaks up into several short pieces. Accordingly, the Sn matrix has grain boundaries to keep the interfacial relations with the less regular Pb-rich phase. On the other hand, the oriented direction of Pb-rich phase arrays changes between the adjacent colonies, the Sn- and Pb-rich phases are all heavily disturbed in the colony boundary region. Along with the increase of cooling rate, the colony size becomes smaller and lamella becomes shorter [Fig. 5(b)], and ultimately the colony disappears, i.e., the “crystallization degree” of solder alloy becomes lower. Correspondingly, the “disordered region” is increased. The structure in “disordered region” is more open; and the diffusion activation energy in it is much small. So the IMC growth rate of the faster cooling rate solder joints is greater than that of slower cooling rate solder joints (see Fig. 4). IMC layer is more brittle than the bulk solder and mismatch in microstructure with Sn–Pb solder and copper pad, during shear cycling, the shear stress is easily concentrated at the interface of solder/IMC layer, formed higher stress regions, increased susceptibility of the joint to cracking (see Fig. 9) [1], [13]. The variation in the roughness (Fig. 3) of the solder/IMC interface should be responsible for the fatigue lifetime difference of
Fig. 6. Optical microstructures of solder bulk reflowed by profile #1.

Fig. 7. Fatigue lifetime \(N_{50\%}\) of solder joints reflowed by different profiles versus square root of aging days.

Fig. 8. Cross section SEM view of initial crack in a solder joint.

Fig. 9. Cross section SEM view of crack in a failed solder joint.

Fig. 10. Cross section SEM view of initial crack in a solder joint.

Fig. 11. Cross section SEM view of crack in a failed solder joint.

nonaged solder joint [6]. The above results mean that the more disordered the solder alloy is, the more serious the tin diffusion is, the thicker of IMC layer is formed during aging, and the larger the variation of solder joint fatigue lifetimes is (see Fig. 7).

IV. CONCLUSIONS

Based on the above analysis, the following conclusions can be reached.

1) By increasing the conveyor speed during reflow, the cooling rate of PBGA solder joints during solidification increased. Heat transmission analysis proves that increase of conveyor speed increases the mean coefficient of the heat transfer, increasing the cooling rate.

2) For nonaged solder joints, it was found that faster cooling rate can improve the solder joint shear fatigue lifetime substantially. And the shear fatigue lifetimes of aged solder joints decrease with extension of aging time; moreover, the lifetime variation of fast cooled solder joints is larger.

3) Faster cooling rate results in a rougher interface between the solder and IMC layer, and less crystallization microstructure of solder alloy. Rougher interface increases the fatigue life of nonaged solder joint.

4) SEM micrographs of the failed solder joints reveal that cracks initiate at acute position near solder pad, then propagate along the interface of solder/IMC layer.

5) During aging, the growth of IMC is a diffusion-controlled process, and the diffusion in disordered region is dominant. So the IMC growth rate of fast cooled solder joints is larger. The growth of IMC layer decreases the shear fatigue lifetimes of aged solder joints.

APPENDIX

CALCULATION OF THE MEAN COEFFICIENT OF HEAT TRANSFER \(h_m\)

The advanced five-zone reflow gas convection oven (BTU VIP-70) was used in this work. During reflow, the conveyor of the oven carried the PBGA assemblies forward. Due to this movement, there was a relative flow of gas in the opposite direction through the solder array. The flow of gas contributed mainly to the heat transfer of solder bumps, and the heat transfer was mainly in the forced convection mode. The free fluid velocity \(u_f\) was the same as the conveyor movement velocity (Fig. 10). If we approximately model the solder bumps as cylinders, for an in-line array (Fig. 11), the mean coefficient of heat transfer \(h_m\) can be calculated as [15]

\[
\frac{h_m d}{k_f} = C(R_e)^n
\]

where constant \(C\) and exponent \(n\) geometric parameters;
The film temperature is defined as

\[ T_f = \frac{T_a + T_\infty}{2}, \quad (A2) \]

The Reynolds number is defined as

\[ Re = \frac{u_{\text{max}} d}{v_f}, \quad (A3) \]

where \( v_f \) is the kinematic viscosity of the fluid, \( u_{\text{max}} \) is the maximum velocity of the fluid at the region of minimum-flow area of width \( S_n - d \) shown in Fig. 11, given by

\[ u_{\text{max}} = \frac{S_n}{(S_n - d)}. \quad (A4) \]

In this work, the solder diameter is taken to be 0.75 mm, and the solder bump pitch \((S_n, S_p)\) is 1.5 mm. So \( S_n/d \) and \( S_p/d \) are both 2. \( C \) and \( n \) in \((A1)\) are 0.229 and 0.632, respectively. We take \( T_a \) and \( T_\infty \) as 175 °C and 150 °C, respectively (see Fig. 1), so the \( T_f \) is 162.5 °C. We take standard values for dry air at atmospheric pressure (the values are not strongly pressure-dependent and may be used over a fairly wide range of pressures) of 160 °C to calculate \( h_m \) [W/(m² · °C)]. The values of \( k_f \) and \( v_f \) are \( 3.64 \times 10^{-2} \) [W/(m · °C)] and \( 30.09 \times 10^{-6} \) (m²/s), respectively. The results corresponding to profile #1, #2, and #3 are 4.2, 8.3, and 11.5, respectively. It can be seen that the mean coefficient of heat transfer \((h_m)\) of profile #3 is about 3 times that of profile #1. Consider the value of \([T_a(t) - T_\infty(t)]\) in \((1)\) is about 10 °C (ref. Fig. 1), the cooling rates per unit area of profile #1 and #3 are 42 and 115 (W/m²), respectively. The difference is considerable.

**REFERENCES**


**S. H. Fan** received the B.Eng. degree and the M.S. degree in material sciences from Huazhong University of Science and Technology (HUST), Wuhan, China, in 1986 and 1989, respectively, and is currently pursuing the Ph.D. degree at the City University of Hong Kong.

From 1989 to 1997, he was a Senior Engineer with the Beijing Institute of Radio Measurement, Beijing, China, in 1998, he was a Research Assistant in the Department of Electronic Engineering, City University of Hong Kong. His current research interests are in reliability study of area array solder joints such as BGA, CSP, as well as no-flow underfill and anisotropic conductive film (ACF) for flip-chip assembly.
Y. C. Chan received the B.Sc. degree in electrical engineering, the M.Sc. degree in materials science, and the Ph.D. degree in electrical engineering, all from the Imperial College of Science and Technology, University of London, London, U.K., in 1977, 1978, and 1983, respectively.

He joined the Advanced Technology Department, Fairchild Semiconductor, as a Senior Engineer, and worked on integrated circuits technology. In 1985, he was appointed to a Lectureship in Electronics at the Chinese University of Hong Kong. Between 1987 and 1991, he worked in various senior operations and engineering management functions in electronics manufacturing (including SAE Magnetics (HK), Ltd. and Seagate Technology). He set up the Failure Analysis and Reliability Engineering Laboratory for SMT PCB, Seagate Technology (Singapore). He joined the City Polytechnic of Hong Kong (now City University of Hong Kong) in 1991. He is currently Professor (Chair) in the Department of Electronic Engineering and Director of the EPA Center. He has authored or co-authored over 140 technical publications in refereed journals and conference proceedings. His current technical interests include advanced electronics packaging and assemblies, failure analysis, and reliability engineering.

C. W. Tang received the B.Sc. degree in mechanical engineering (with first class honors) and the M.Sc. degree (with distinction) from the University of Hong Kong, and is currently pursuing the Ph.D. degree in advanced packaging of flip chip assemblies at the City University of Hong Kong.

His research interests are advanced electronics manufacturing technology and reliability issues of no-flow underfill and anisotropic conductive film (ACF) of flip chip assemblies.


From 1974 to 1985, he was a Research Officer at the Central Electricity Research Laboratories, Surrey, U.K. In 1984, he was appointed Project Leader of the Remaining Life Study Group and a member of the Remanent Life Task Force, Central Electricity Generating Board, U.K. He returned to Hong Kong and joined the City University of Hong Kong (previously called City Polytechnic of Hong Kong) in 1985. He is now Chair Professor of materials science, Director of the Materials Research Center, and Associate Dean of the Faculty of Science and Technology. He has published over 80 papers in international refereed journals. He has acted as consultant for the Hong Kong Government and local industries on over 40 cases of accidents/disputes involving the failure of metallic components.