Thermal-Mechanical Analysis of a QFN Stacked-Die Leadframe under Reflow Process

S.Abdullah, M.F.Abdullah, A.K.Ariffin, Z.A.Aziz and M.J. Ghazali

Abstract— **The copper-based leadframe is practically proven effective in the thermal and reliability of a Quad Flat No Lead (QFN) three dimension (3D) stacked-die semiconductor package. Reducing the copper thickness is understood to present various thermal and reliability failure mode and mechanisms, such as die cracking and delamination. However, no in-depth study has been pursued to determine the capability of achieving the product requirements in terms of thermal and reliability in a 3D stacked-die package. The drive towards a Die-Free Package Cost (DFPC) reduction has led the authors to study the used of a thin leadframe in a QFN 3D stacked-die. Hence, the work presents basis for the qualification of a thin leadframe design, and also to demonstrate the thermal and reliability performance. Finally, an extensive virtual thermal–mechanical prototyping has to be achieved in order to understand the physics of materials during the assembly and reliability testing of a 3D stacked-die package with a thin leadframe. This design rule was found to be developed in order to prevent a die crack occurrence between die and leadframe in the semiconductor package.**

***Index Terms*— 3D Stacked-die, Design, Leadframe, QFN, Stress, Thermo-Mechanical.**

I. INTRODUCTION

The reliability of microelectronic packages a major concern in the electronic industries. Thermal-mechanical stress failure in packaging materials is one of the leading causes of the microelectronic packaging component failure and reliability issues. With the periodical switching on and off in the circuit and the variety of environment temperature, the packaging component will experience thermal cycles. Because of the coefficient thermal expansion (CTE) mismatch of the constituent materials, the package undergoes periodic thermal stress and strain [1]. Epoxy Molding Compound (EMC) is widely used as encapsulating material for copper leadframe and die in electronic packaging application. EMC is used because it has a good thermal-mechanical properties and lower cost in terms of production. However, the leadframe and encapsulating materials are prone to thermo-mechanical failures and low-cycle fatigue is often prominent [2].

During assembly process, residual stresses will be introduced in the package. The residual stress can impose the impact for the package reliability in many aspects. During the temperature cycling, thermal stress due to the mismatch of coefficients thermal expansion (CTE) between dissimilar materials in the package may cause the initiation of crack and propagation, and finally it may result in the package failure [3]. With the decrease in electronic component volume and the increase in the density of input and output connection, the testing to the actual electronic component thermal-mechanical performance becomes more difficult. In solving the issues, finite element analysis (FEA) becomes an important tool to analyze the thermal-mechanical reliability of electronic devices and assembly [4]. Though a great deal of research work on the solder fatigue has been published, not so much study on the thermo-mechanical fatigue of packaging polymers has been done [5, 6].

This paper uses the result of finite element modeling for simulating the actual packaging process and the temperature strep condition in the infra red (IR) reflow process for the QFN package. In addition, a study on the process-induced residual stress and the thermal stress during thermal cycling, for which it may cause thermal-mechanical stress on the different leadframe thickness also been done.

II. METHODOLOGY

A. Materials properties and constitutive behaviour

The input of material properties of the finite element analysis (FEA) application are listed in Table 1. The behaviour of eutectic solder joints is modelled as temperature dependent elastic-plastic and rate-dependent creep. The temperature dependence of the Young's modulus (E) is mathematically defined by the following equation [2]:

$$E(T) = 35366 - 151T \quad (1)$$

where the temperature T is in the unit of Celsius (°*C)*. The solder is assumed to have an elastic-perfect plastic behaviour. The temperature dependent yield stress (σ_y) is described by the following expression:

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$$\sigma_y(T) = 49.2 - 0.097T \quad (2)$$

Table 1: Material properties of the designated QFN package.

Material	E (GPa)	Poisson's Ratio	G (GPa)	CTE (ppm/°C)
Leadframe	120.70	0.11	52.500	16.63
Epoxy	7.50	0.25	0.340	8.00
Mother Die	28.00	0.26	8.000	3.61
DAF	1.66	0.26	0.038	17.00
Daughter Die	28.00	0.26	8.000	3.61
Mold Compound	8.00	0.35	7.000	3.90

The creep behaviour ($\dot{\varepsilon}_{cr}$) for a given material shows a different mechanisms that may be operative at different temperature values and stress levels. In order to gain more insights into the time-dependent properties of the sample materials, it is desirable to obtain the relationship between the nanoindentation strain rates (ε) and the average indentation stress (σ) during the holding time. The creep behaviour mathematically defined as following:

$$\dot{\varepsilon}_{cr} = C_1\left(\frac{E}{T}\right).\left[\sinh\left(\frac{\alpha\sigma}{E}\right)\right]^n.e^{\frac{Q}{KT}} \quad (3)$$

The Epoxy Molding Compound (EMC) that being used in the QFN package is assumed a time-temperature dependent viscoelastic material. The shear modulus is modelled with a fifteen term of the Maxwell model (*G(t)*) as given in the following expression:

$$G(t) = G_\infty + \sum_{i=1}^{n} G_i.e^{-t/\tau_i} \quad (4)$$

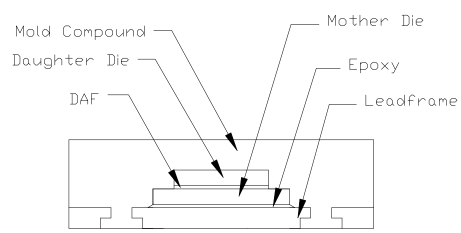
where G_∞ is the equilibrium shear modulus, τ_i and G_i, are the relaxation time and stiffness coefficient corresponding to the term in the Maxwell model, respectively. The temperature effect is considered with the assumption of having a thermorheologically simple material. This situation can be explained using the William-Landel-Ferry (WLF) equation, i.e:

$$\log a_T = \frac{-C_1\left(T - T_{ref}\right)}{C_2 + \left(T - T_{ref}\right)} \quad (5)$$

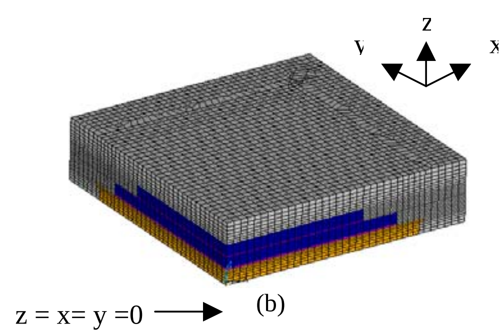
where, T_{ref}, is the reference temperature, and both C_1 and C_2, are the material constants. For this case, the Possion's ratio is assumed to be a constant value, i.e. 0.30 [1]. In order to complete the analysis of this paper, the ANSYS® software package was used to simulate the QFN package computational analysis based to the listed mathematical model.

B. Geometry and FEM mesh

For the finite element modeling purposes, the QFN model was designed by a fully matrix QFN 3D stacked-die package. Two models of QFN packages which were in the same dimension have been simulated for the purpose of this study. The schematic diagrams of the QFN 3D stacked-die package are illustrated in Fig. 2(a) and 3(a). Both units were in the same size and the package thickness is 0.85 mm. The unit with the above said dimension was chosen as it can give high reliability performance. However, the differences between two selected models were only on the thickness of leadframe and mold cap. Fig. 2 shows the leadframe thickness of 0.20 mm and the mold cap thickness of 0.65 mm. On the other hand, Fig. 3 shows the leadframe thickness of 0.15 mm and the mold cap thickness of 0.70 mm. In these QFN units, epoxy, mother die, die attach film (DAF) and daughter die were all fabricated using the same materials.



(a)



(b)

Fig. 1: (a) A schematic diagram of the QFN package for leadframe thickness of 0.20 mm, (b) FE mesh of the QFN package

Using ANSYS®, the FEA modeling was performed onto a quarter model of a QFN structure, and the FE mesh of this model is presented in Fig. 1(b) and 2(b). The applied boundary conditions were based on the origin coordinate (*z = x = y = 0*) and the nodes along the symmetric axis are based on the symmetric boundary conditions.

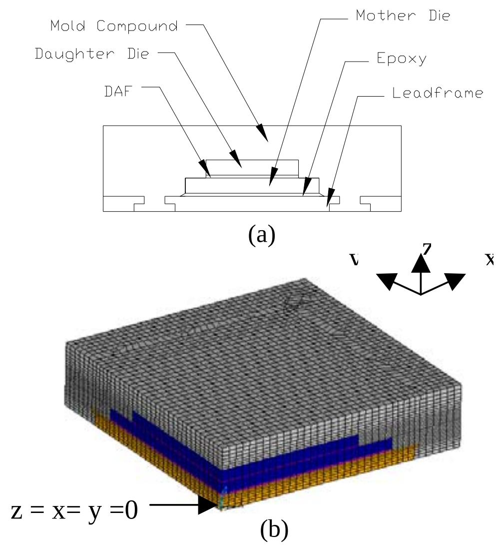


Fig. 2: (a) A schematic diagram of the QFN package for leadframe thickness of 0.15 mm, (b) FE mesh of the QFN package

C. Thermal loading

In order to simplify the analysis of this paper, the thermal loading history includes the cooling down process from the curing, reflow soldering and three temperature cycles. Table 2 shows the temperature profile used in the entire simulation [7]. The distribution of this profile is illustrated in Fig. 3. According to the JEDEC standard [7], the information in Table 2 and Fig. 3 are important for the package testing. It is because of the similarity indication between the reflow tests to the actual application.

Table 2: Process Reflow of QFN package [7]

Profile Feature	**Pb-Free Assembly**
Average ramp-up rate (Ts_{max} *to* T_p)	3°C/second max.
Preheat	
– minimum temperature (Ts_{min})	150°C
– maximum temperature (Ts_{max})	200°C
– time (ts_{min} to ts_{max})	60-180 seconds
Time maintained above:	
– temperature (T_L)	217°C
– time (t_L)	60-150 seconds
Peak/classification temperature (T_p)	260 + 0°C
Time within 5 °C of actual peak temperature (t_p)	20-40 seconds
Ramp-down rate	6°C/second max.
Time 25 °C to peak temperature	8 minutes max.

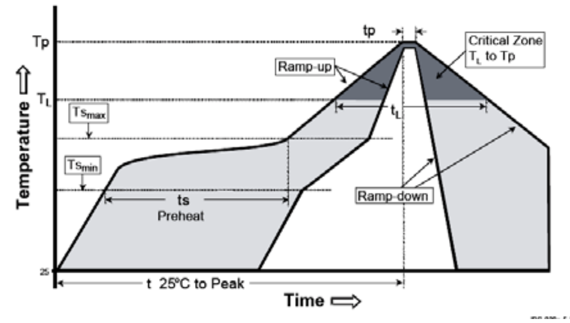


Fig. 3: Classification Reflow Profiles [7]

Referring to Fig. 3, the reflow process is not longer than four hours and also to three times cycles of the appropriate reflow conditions, and this procedure has been defined in Table 2 and Fig. 3. This condition is happened after the removal from the temperature and humidity chamber. For this case, the optimum period of the reflow process was related to the actual IC package application. If the timing between the removal from the temperature and humidity chamber and the initial reflow cannot be met, then the parts must be rebaked and resoaked according to bake the sample for 24 hours, with the minimum temperature of about 125°C. This step is intended to be performed in order to remove moisture from the package so that it will be 'dry'. The moisture soak meant that a package is placed in a clean, dry, shallow container so that the package bodies do not touch or overlap each other. At all time parts for etch temperature it should be handled using proper Electronic Static Discharge (ESD) procedures. The time between reflows shall be five minutes at the minimum and 60 minutes at the maximum [7].

III. RESULTS AND DISCUSSIONS

The IR reflow process has 6 steps for difference thermal loading and 1 step for stress free process. Because of the higher curing temperature value (260°C) and the mismatch of the coefficients of thermal expansion between dissimilar materials, the residual stress in the leadframes is already induced at the initial stages of the thermal loading. Table 3 shows the numerical simulation result for displacements and Table 4 shows the results of the von-Mises-stresses for the leadframe thickness of 0.20 mm and 0.15 mm. In this study, the focus is more on the stress that was distributed between two types of leadframe thickness.

Generally, semiconductor industries have a relevant standard for the reliability testing of a package, for example, the IR reflow process and it has been applied after the Moisture Sensitivity Level (MSL) procedure. This process flow involved the die mounting, wire bonding, molding and singulation. During the test, the EMC elements were deactivated in die attach process, i.e. at 175°C, and this temperature is a reference for the minimum stress temperature [1-3]. The related information for this test is listed in Table 3. In addition to the process, the EMC element was reactivated at the molding temperature (175°C), and it was then cooled to 25°C. It meant that the element birth and death option can meet the simulation equipments. At the die mounting and temperature, the package components are assumed to be stress free.

Fig. 4 shows the displacement (µm) between two different leadframe thicknesses versus step temperature condition. In this figure, the starting step condition is Step 1 and the displacement for both leadframe types was in the negative value. This condition showed that the leadframe was under shrink, indicating the shrinking occurrence of the leadframe thickness of 0.20 mm has more superior compared to the thickness 0.15 mm. Step 2 shows no different (in term of shrinking characteristics) between both leadframe types, and it is because of the step 2 temperature was nearer to the reference temperature. In step 3, no displacement has been found since the stress free condition was within this temperature range. In step 4, the analysed leadframe units were under expanse and the displacement was found to be at the positive value. It is because of the temperature of step 4 were higher than the reference temperature, indicating that this leadframe absorbed more heat. In step 5, the displacement for the leadframe thickness 0.20 mm was higher (which is 0.461 µm) than leadframe 0.15 mm (0.427 µm). In step 6, the maximum displacement is presented and the maximum temperature was found to be at 260°C for the IR reflow. IN the step 7, finally, it has been shown that the higher shrink condition can lead to the cracking occurrence in the QFN package. In the analysis, the 0.2 mm leadframe has the maximum expanse reduction in a short time.

In this case, the 0.20 mm leadframe thickness has more displacement compared to the 0.15 mm leadframe thickness. The larger displacement of the leadframe can affect to the failure for other component in a package, such as epoxy, mother die, die attach film, daughter die and mold compound. From the simulation, therefore, it can be concluded that the 0.2 mm leadframe thickness can give more risk in die cracking occurrence and also the delamination effect.

Table 3: Result stress for IR Reflow QFN packages in displacements used leadframe 0.20 mm and 0.15 mm

Step/ Stress	Stress Distribution	
	Displacement of 0.20 mm leadframe thickness (µm)	*Displacement of 0.15 mm leadframe thickness (µm)*
1) Ambient temperature	-1.180	-1.030
2) Preheat T_s min at 150°C	-0.393	-0.343
3) Stress Free at 175°C	0.000	0.000
4) Preheat T_s max at 200°C	0.292	0.261
5) Time Maintained, T_L max at 217°C	0.461	0.427
6) Peak/Classification Temperature, T_p at 260°C	0.985	0.865
7) Finish IR Reflow at 25°C	-1.180	-1.030

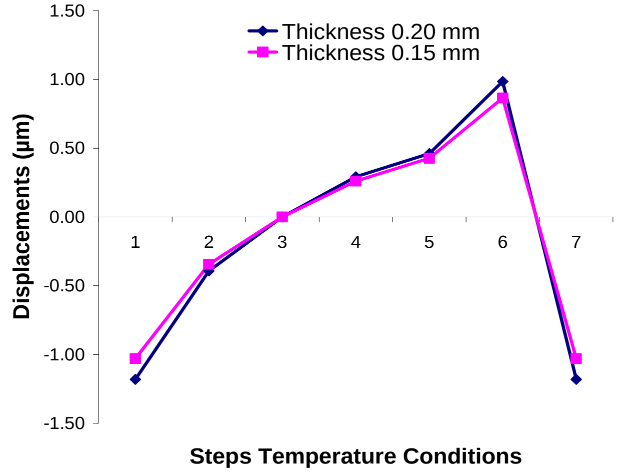


Fig. 4: A plot of Displacement for different leadframe thickness vs the stages (step) of temperature conditions

Table 4: Result stress for IR Reflow QFN packages in von Mises stress used leadframe 0.20 mm and 0.15 mm

Step/ Stress	Stress Distribution	
	von Mises stress of 0.20 mm leadframe thickness (GPa)	*von Mises stress of 0.15 mm leadframe thickness (GPa)*
1) Ambient temperature	1.020	0.974
2) Preheat T_s min at 150°C	0.277	0.264
3) Stress Free at 175°C	0.003	0.025
4) Preheat T_s max at 200°C	0.219	0.206
5) Time Maintained, T_L max at 217°C	0.323	0.305
6) Peak/Classification Temperature, T_p at 260°C	0.664	0.604
7) Finish IR Reflow at 25°C	1.020	0.970

The von Mises stress, σ_v is the scalar function of the stress tensor that gave an approximation for the overall magnitude' of the tensor. It allows the onset and amount of plastic deformation under triaxial loading to be predicted from the results of a simple uniaxial tensile test. It is most applicable to a ductile material analysis. The von Mises stresses can then be used to predict failure by ductile tearing. However, it is not appropriate for failure by crack propagation or fatigue, which depends on the maximum principal stress.

In this case, the maximum value of the von Mises stress was obtained at the 0.20 mm leadframe thickness, and it can be extracted from the information of Fig. 5. In this figure, two steps have been found to have the maximum value of von Mises stress, and they are step 1 and 7. The results of step 1 and 7 might be caused by the difference between the reference temperature and the ambient temperature, for which these temperature values were higher compared to another. It was also observed that higher thickness gave higher value of von Mises stresses. However, the maximum stress value was 0.974 GPa, and it can be accepted because of this value was lower than the Young's modulus of the QFN materials (refer to Table 1).

The 0.15 mm leadframe is a new design for a semiconductor package, which it seems to be better than 0.20 mm leadframe. In actual condition, the fabrication cost of the 0.15 mm leadframe is higher than the 0.20 mm leadframe. From the simulation result, it is suggested that the reliability of 0.15 mm and 0.20 mm leadframes were slightly similar with respect to the deformation on the displacement and also the von Misess stresses.

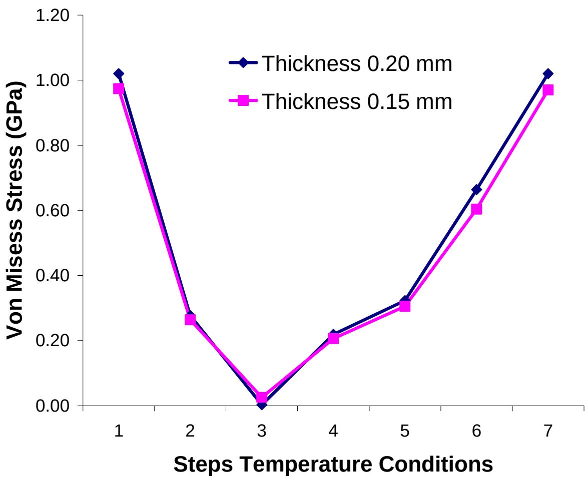


Fig. 5: A plot of von Mises stress for different leadframe thickness vs the stages (step) of temperature conditions.

CONCLUSION

A study on the packaging process induced initial stress-state of a selected QFN package was presented in this paper. The IR reflow are considered to be the temperature dependent elastic-plastic and rate dependent creep behavior. The viscoelastic behaviour of EMC during and after reflow process is simulated subsequently followed by temperature cycling simulations.

From the simulation results, it has been showed that the thin leadframe can reduce the stress value within the QFN package. In this aspect, however, the increment of stress is not too much difference from the stress performed by the leadframe thickness of 0.20 mm and leadframe thickness of 0.15 mm. The stress distribution obtained for the second leadframe with 0.15 mm thickness was still under the Young's modulus value.

In order to produce a good configuration of a QFN package, it is suggested that to select a material must based on coefficients of thermal expansion (CTE) material which is not too much difference so that it can perform a lower and better stress value. The residual stresses occur due to the mismatch between dissimilar materials during the reflow soldering process. At the end of the reflow process, the tensile stress of centre surface in EMC is at the highest level, the centre surface of leadframe is the possible failure site for delamination and die-crack.

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