Creep Damage of BGA Solder Interconnects Subjected to Thermal Cycling and Isothermal Ageing

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Abstract – Solder joints of electronic components are the most critical part of any electronic device. Their untimely failure during the system’s operation often culminates in catastrophic failure of the device. The determination of creep damage in electronic component solder joint is vital to the prediction of crack initiation and prevention of premature failure. This paper presents the creep damage in solder joints in a ball grid array (BGA) soldered on a printed circuit board (PCB) and subjected to thermal cycling as well as isothermal ageing. ANSYS 19.0 package is employed to model the isothermal ageing at -40, 25, 75 and 150°C temperatures for 45 days. Standard temperature cycle profile is used to simulate the effect of the coefficient of thermal expansion (CTE) mismatch on the bonded materials in the BGA component. The solders studied are lead-based eutectic solder alloy and lead-free SAC396, SAC387, and SAC305. Based on the results obtained for the stress, strain rate, deformation rate and strain energy of the solders, the research investigation advises on the most effective solder for achieving improvement in the thermo-mechanical reliability of solder joints in BGA soldered on PCB.

Keywords: strain, thermal cycling, isothermal ageing, strain energy, ball grid array (BGA), thermo-mechanical

1.0 Introduction
In electronic assemblies, solder joints are subjected to thermal, electrical and mechanical cycling. These cyclic loadings lead to the fatigue failure of solder joints involving crack initiation, crack propagation, damage accumulation, and failure. Thermal cycling and ageing lead to meaningful changes in the microstructure and mechanical behaviour of solder joints used in safety-critical applications such as aeroplane, defence, oil and gas drilling applications, automobile, medical devices, power grids and so forth. Because solder joints are applied at high temperatures and small, their reliability is of fundamental interest to electronics manufacturing engineers and industries. The capability of solder joints to remain in conformance with their mechanical, electrical and visual specifications over a specified duration, under a specific set of operational provisions is referred to as solder joint reliability. Reliability of these joints is determined by multiple factors such as shear strength, creep resistance, drop shock, thermal fatigue and vibration resistance. Due to the adoption of the Restriction of Hazardous Substances (RoHS) directives on July 2006, by the European Union (EU), there have been new progress and developments in lead-free solders as a replacement for the conventional lead-based solders for application in the electronics manufacturing industries [1-5]. Amongst the lead-free solders investigated, Sn-Ag and Sn-Ag-Cu (SAC) based solders offer the most promising characteristics as replacement of lead-based solders [6-7]. Introduction of new lead-free solders added a new dimension to reliability concerns in electronic devices. Solder joints provide the necessary mechanical, electrical and thermal connections between package elements and substrate in electronics packaging. The integrity of solder joints is a significant reliability interest in microelectronic packages. Thermal variations induced by either environmental changes or power transients, with the resulting coefficient of thermal expansion mismatch between the various package materials, results in time and temperature-dependent creep deformation of solder. This deformation accumulates with repeated cycling and ultimately causes solder joint cracking and interconnect failure. To reduce development values and maximise reliability performance, simulation analysis (FEA) is a prerequisite throughout the design and development stage of a microelectronic package. Moreover, these joints serve as the weakest links in the overall package in the sense that if any of these joints fail, then the whole system could eventually fail and stop functioning. From a structural point of view, solder joints are complex, heterogeneous and dynamic systems, and it is vital to consider several elements of the solder structure, to know their thermo-mechanical behaviours. While in operation, electronic products are exposed to a variety of application conditions such as vibration, which can induce impact and fatigue failures. Thermal ageing of solder joints, on the other hand, produces changes in the solder joint microstructure and could trigger creep failure [8-9]. Awareness and knowledge of the failure mechanisms of these systems are necessary for preventing accidents [10] and the cyclical variation of thermal stress effects solders joint thermal fatigue failure. Throughout thermal cycling, creep is the primary tool of thermal deformation fatigue failure. With ambient temperature changes (e.g. temperature periodicity rises and fall) or part emits heat (e.g. systematic power on and off), solder joints will produce thermal stress. In the development of thermal cycling, creep is the critical process of thermal deformation fatigue failure [11].

2.0 Methodology
2.1 Thermal Cycling Test
2.1.1 Convergence and Mesh Independence Study
A mesh convergence study verifies that the FEA model has converged to a solution. It also justifies mesh independence
and additional refinement is unnecessary. It does not take much for an FEA to produce results. Nevertheless, for results to be valid, we must show that results converge to a solution and are independent of the mesh size. The results of an FEA model must be independent of the mesh size. A convergence study ensures that the FEA model captures the behaviour of the system while reducing solve time. The convergence plot in mesh refinement is presented in Fig. 1 for the mesh convergence study for SAC305 sub-modelled component. A fine mesh is used in the region of high-stress gradients, and coarse mesh is ignored. It can be seen that the more the mesh becomes finer, it does require considerably high CPU simulation solve time. The following necessary steps are needed to perform a mesh convergence study: (1) Generate a mesh utilising the fewest, moderate quantity of elements and examine the model; (2) Recreate the mesh with a denser element configuration, re-analyse it, and analyse the outcomes to those of the earlier mesh; (3) Continue increasing the mesh density and re-analysing the model until the results converge adequately to a solution.

2.1.3 Geometrical and Mesh Models
The BGA package includes solder ball, silicon (Si) die substrate, copper (Cu) pad and epoxy-resin (FR-4). The parameters and package dimension of the lead-free solder BGA are shown in Table 1 & 2: Fig. 2(a & b) shows the full model assembled components and the quarter (meshed) view of the assembled component used for the FEA simulation.

Solder materials are susceptible to significant creep deformations in harsh high-temperature environments such as oil exploration, automotive, avionics, and military applications. Also, degradations will happen in the creep responses of lead-free solder alloys when they are exposed to long-term thermal ageing during product applications at high temperatures. Fahim et al. (2016) [12] examined high temperature creep response of lead-free solders. In their work, they characterised the high temperature creep behaviours of SAC405 and concluded that SAC alloys were more resistant to creep at high temperature. Creep deformation has become a dominant deformation in electronics devices and happens when going above 0.4 and also occurs at reasonably low temperatures [13-14].

2.1.2 Basic Assumptions and Analysis Methodologies
- Every interface of the materials is assumed to be in contact with each other totally.
- All the materials were modelled as linear elastic and isotropic materials except the solder and PCB which are simulated using the Garofalo creep relations and orthographic materials respectively.
- All materials including the solder joint were assumed homogeneous at load steps.
- The assemblies were assumed to be a stress-free state at room temperature of 22°C, which was also the starting temperature of the thermal cycle loading.
- The initial stress in the assemblies which may be accumulated from the reflow soldering process is neglected, and all contacting surfaces are assumed to be bonded with perfect adhesion.

The thermo-mechanical response of the solder joint is very vital in the design of a reliable electronics circuit board assemblies, and creep plays an essential role in the damage mechanism of solder joints. Under different operating conditions, solder joints experience several categories of loading conditions which include thermal cycling, vibration and shock, over-stress, and cycle bending of circuit boards. As a result of every loading condition, solder may creep or rupture. Creep are considered as the principal deformation mechanisms in the solder joints [15] and are examined critically in this section. Several creep constitutive models have been reported. The Garofalo-Arrhenius constitutive relation has been adopted for this research because its’ usage has an outstanding capability of improving the accuracy of prediction of the magnitude of damage in solder joints [16-17].
2.1.4 Garofalo-Arrhenius creep model

Creep is a function of temperature, plasticity, and time-dependent complex deformation and its’ effect is more significant in solders alloyed material at high homogeneous temperature. The research by Amalu & Ekere (2016) [47] who investigated the modelling evaluation of Garofalo-Arrhenius creep relation for lead-free solder joints in surface mount electronic component assemblies. They used different creep parameters in Garofalo-Arrhenius constitutive creep relation and used four set of values, proposed by Lau (2003) [19], Pang et al. (2004) [20], Schubert et al. (2003) [21] and Zhang et al. (2003) [22], to generate four hyperbolic sine creep relations and proposed a paradigm for selecting suitable constitutive model(s) for accurate prediction whilst suggesting the development of new solder constitutive relations. The Garofalo creep constitutive constants used for the investigation is presented in Table 3.

Ramachandran & Chiang (2017) [23] studied the feasibility evaluation of creep model for failure assessment of solder joint reliability of wafer-level packaging. They developed a new creep model based on the assumptions that an instantaneous steady-state creep form eliminates the evolution term, resulting in a creep equation with four parameters and the proposed model has a similar vital statement similar to that of the well-known hyperbolic sine model. The model significantly broadens the application of the hyperbolic model. They used a WLCSP on PCB and performed thermal cycling experiments in ESPEC TCC-150. The steady-state creep is the dominant deformation experienced by solder alloys. This can be quantitatively estimated, and a series of constitutive models were proposed. The two models that are widely accepted for the characterisation of solder alloys by considering the diffusion-controlled creep deformation mechanism:

### Table 1: Parameters of Lead-Free BGA Solder Architecture

| Balls | Ball Matrix | Pitch | Size (mm) | Substrate | Part Number | Reference | Quick view |
|-------|-------------|-------|-----------|-----------|-------------|-----------|------------|
| 36    | 6x6         | 0.5mm | 3mm       | Silicon (Si) | WLP36T.5C-DC067D | TopLine (2016) [24] |

### Table 2: Package Dimensions

| Package | Dimensions (mm where applicable) |
|---------|----------------------------------|
| PCB     | 5 × 5 × 1.6                      |
| Solder Mask Thickness | 0.05 |
| Substrate (Silicon) | 3 × 3 × 0.35 |
| Cu Pad Diameter | 0.36 |
| Cup Pad Thickness | 0.02 |
| Die (Epoxy-Resin) | 5 × 5 × 0.05 |
| Solder Ball Height | 0.24 |
| Solder Balls | 36 |
| PCB Mask | 0.05 |

### Table 3: Creep Constitutive Constants for Solder Alloys

| Constitutive Model | Solder Alloy          | Reference | $\frac{1}{A(s)}$ | $\alpha$(MPa$^{-1}$) | n | Q (KJ/mol) |
|--------------------|-----------------------|-----------|------------------|----------------------|---|------------|
| Garofalo sine-Hyperbolic | Sn63Pb37 | Wiese, et al. (2001) [33] | 1.0 × 10 | 0.1000 | 2.0 | 44.90 |
|                       | SAC305 | Vianco (2006) [34] | 2.63 × 10$^3$ | 0.0453 | 5.0 | 52.40 |
|                       | SAC387 | Schubert, et al. (2003) [35] | 3.20 × 10$^4$ | 0.0370 | 5.1 | 65.30 |
|                       | SAC405 | Wang, et al. (2005) [47] | 1.7 × 10 | 0.14 | 4.2 | 55.00 |
|                       | SAC396 | Lau, et al. (2003) [19] | 4.41 × 10$^5$ | 0.0050 | 4.2 | 45.00 |
Table 4: Materials Properties

| S/No | Material                  | Reference                      | Young’s Modulus (GPa) | C.T.E (ppm/°C) | Poisson’s Ratio | Shear Modulus (GPa) |
|------|---------------------------|--------------------------------|-----------------------|-----------------|-----------------|---------------------|
|      |                           |                                | $E_x$ | $E_y$ | $E_z$ | $\alpha_x$ | $\alpha_y$ | $\alpha_z$ | $v_{xy}$ | $v_{xz}$ | $v_{yz}$ | $G_{xy}$ | $G_{xz}$ | $G_{yz}$ |
| 1    | Silicon(Si) Die           | TopLine (2016) [24]            | 110.0 | 2.60  | 0.24  | 50.8        | 1.48       | 4.81     |           |           |           |           |           |           |           |
| 2    | PCB Mask                  | Zahn (2002) [39]               | 4.14  | 30.0  | 0.40  | 1.48        |            |           |           |           |           |           |           |           |           |
| 3    | Cu Pad                    | T.Nguyen, et al. (2010) [40]   | 129.0 | 17.0  | 0.34  | 48.1        |            |           |           |           |           |           |           |           |           |
| 4    | PCB                       | Amalu & Ekere (2016) [18, 47]  | 27.0  | 27.0  | 22.0  | 14.0        | 15.0       | 0.17     | 0.20     | 0.17     | 27.0      | 22.0      | 27.0      |           |           |
| 5    | Epoxy-Resin (FR-4)        | TopLine (2016) [24]            | 29.9  | 25.1  | 70.0  | 12.0        | 15.0       | 0.16     | 0.14     | 12.9     |           |           |           |           |           |
| 6    | Sn63Pb37                  | Long, et al. (2018) [36]       | 56.0  | 20.0  | 0.30  | 21.5        |            |           |           |           |           |           |           |           |           |
| 7    | SAC305                    | TopLine (2016) [24]            | 51.0  | 23.5  | 64.0  | 0.40        | 18.8       |           |           |           |           |           |           |           |           |
| 8    | SAC387                    | Beyer, et al. (2016) [37]      | 32.0  | 20.0  | 0.42  | 15.7        |            |           |           |           |           |           |           |           |           |
| 9    | SAC405                    | J.Eckermann, et al. (2014) [48]| 44.6  | 23.2  | 0.30  | 16.5        |            |           |           |           |           |           |           |           |           |
| 10   | SAC396                    | Stoyanov, et al. (2009) [38]   | 43.0  | 23.2  | 0.30  | 16.5        |            |           |           |           |           |           |           |           |           |

2.1.5 Material Properties and Parameters

- **Dorn Power Law** [49]
  \[
  \varepsilon = A \sigma^n \left( \frac{Q}{RT} \right)
  \]
  Equation 1

- **Garofalo Hyperbolic Sine Law** [50]
  \[
  \varepsilon = A [\sinh(n \sigma)]^n \left( \frac{Q}{RT} \right)
  \]
  Equation 2

Where $\varepsilon$ is creep strain rate, $A$ is a material constant, $n$ is a multiplier of hyperbolic-sine law, which is obtained from curve fitting to experimental data by using linear and nonlinear least square regression, $\sigma$ is the applied shear stress, $n$ is the stress exponent which can be determined from creep deformation map, it can be found that the deformation mechanism is dislocation creep, so $n$ is between 2 and 7. $Q$ is the activation energy, $R$ is the universal gas constant, and $T$ is the temperature in Kelvin. The models show that the steady-state creep strain rates are strongly stressed and temperature-dependent.

2.1.6 Finite Element Model and Methodology

A 3D FE meshed model of the assembly of the BGA on PCB components is shown in Fig. 2(b) which was created using SolidWorks. The FE model was input into ANSYS software R.19.0 where the static structural response to cyclic induced thermal loads was simulated. The default mesh was not used for the simulation process because the symmetry of the structure was not harnessed; therefore, the shape of the solder balls after generating a mesh look deformed, consequently getting the correct and adequate simulated result will be inhibited. The meshed components part of the solder balls undergoes mesh convergence to arrive at a converged solution. Except for the PCB, the properties of all other materials are considered to be linear and temperature-dependent. The material properties used are obtained from several works of literature. The critical materials used in the assembly in mounting the BGA on PCB are solder alloys, Copper Pad, Epoxy-Resin (FR-4), Solder mask and Silicon (Si) die. The components assembled does not contain the Intermetallic compounds (IMC) because the effect is assumed not to have any influence on the research outcomes. All the materials were modelled as linear elastic and isotropic substances except the PCB and the solder alloys, which was simulated using the orthographic materials and Garofalo creep relations respectively. The material properties used for the FEA simulation experiments are presented in Table 3:

2.1.7 Loading and Boundary Conditions

In implementing the FE Analysis, the ambient temperature cycle is external loading. The FE models were subjected to six complete ATC’s in 36 steps. The thermal cycling temperature is from -40°C to +150°C with 15°C/min ramp, and 600s dwell based on IEC 60749-25 temperature cycling [27] and JEDEC Standard JESD22-A104D [28] as shown in Fig. 3 was used. The quarter assembly components were first heated from room temperature 22°C which is the starting temperature in thermal cycle loading with constant heating rate. They are also
Table 5: Composition of eutectic and SAC solders test samples

| Sample | SAC Alloys | Composition       | Typical Melting Temperature (°C) | Recommended by |
|--------|------------|-------------------|----------------------------------|----------------|-----------------|
| 1      | SAC305     | Sn-3.0Ag-0.5Cu     | Solids: 217°C                     | JEITA          | (Japan)         |
|        |            | [32] Liquidus: 220°C|                                  |                |                 |
| 2      | SAC387     | Sn-3.8Ag-0.7Cu     | Solids: 217°C                     | EU             |                 |
|        |            | [30] Liquidus: 219°C|                                  |                |                 |
| 3      | SAC405     | Sn-4.0Ag-0.5Cu     | Solids: 217°C                     | Global         |                 |
|        |            | [44] Liquidus: 22°C |                                  |                |                 |
| 4      | SAC396     | Sn-3.9Ag-0.6Cu     | Solids: 217°C                     | iNEMI          | (USA)           |
|        |            | [22] Liquidus: 221°C|                                  |                |                 |
| 5      | Lead-based | 63Sn-37Pb          | Solids: 183°C                     | Eutectic Solder| (Standard)      |
|        | Eutectic   | [44] Liquidus: 183°C|                                  |                |                 |

assumed to be at a homologous temperature at loads steps. The temperature loading started from 22°C, dwelled at -40°C at the rate of 15°C/min, and ramped up to 22°C for the 1,380s and excursion temperature (ET) of 150°C for 1,908s where it dwelled for 600s. The composition of lead-free SAC alloys and the lead-based eutectic solder are shown in Table 5. Applications used for this profile are the automotive underhood, semiconductors in power supply controllers and military [25]. The assemblies were supported such that the conditions of the structure at the supports are:

At the PCB base, $y = 0$, and $u(y) = 0$;
Top surface $u(y) = 0$, $u(x)$ and $u(z)$ are free.
The $u(x)$, $u(y)$ and $u(z)$ represent the displacement in the $x$, $y$ and $z$ directions respectively. The bottom surface of the PCB was fixed in $Y$ direction and displaced in the $X$ and $Z$ directions.

The application of six ATC generates relevant data which facilitate a more reliable conclusion of the response of the solder joints to the induced loads. Furthermore, data acquired from this investigation can be used for enhanced design and better-quality invention of solder interconnections in BGA assembly for improved thermo-mechanical reliability. Work carried out by Ma et al. (2006) [29] established how the creep resistance of SAC solders decreases with an increase in time and temperature during isothermal ageing. They examined a full effect of ageing on the creep behaviour of lead-free solders with particular focus on SAC305 and SAC405. They also conducted other investigative experiments for varying temperature duration from 3 – 63 days at room temperature. Ma et al. (2007) [30] also investigated the influence of elevated temperature ageing on the reliability of lead-free solder joints. The researchers stated that the lead-based eutectic and lead-free SAC solder samples were aged at various intervals from 0 – 6 months at several elevated temperatures (80,100,125 and 150°C). Analogous creep test was performed with the eutectic solder sample (63Sn-37Pb) for evaluation and validation of results purposes.

3.0 Thermal ageing test of solder joint

The influence of thermal ageing on the evolution of the solder joint cannot be underestimated. The behaviour of lead-free solder joints in electronics assemblies is continually evolving when exposed to isothermal ageing and thermal cycling environments. The study has investigated both phenomena during the short- and long-term ageing of solder joint in harsh environments. For this research, we have considered creep test temperature of -40°C, 25°C, 75°C and 150°C for 45 days (64,800 mins) of ageing test for FE simulation and experimentally. The plot results obtained in the research are presented in Fig. 4 to 7 showing that SAC396 has the lowest accumulated values for stress, strain rate, strain energy and deformation rate.

The work carried out by Sabbah, et al. (2017) [31] studied the high-temperature ageing of microelectronics assemblies with SAC solder joints. They investigated the failure mechanism and microstructure evolution of solder-free (SAC) solder joints at a maximum temperature of 175°C. It is found that no new failure mechanisms are triggered and that ageing tests for solder can be accelerated at 175°C. In particular, the growth
rate of the interfacial IMC is found to be consistent with that observed at lower temperatures.

In conclusion, it was found that the joints degrade rapidly, especially in cycling conditions. However, the ageing tests performed at 175°C did not show any new failure mechanism compared to previous results obtained at lower temperatures. Therefore, it is possible to run ageing tests at 175°C on SAC soldered assemblies to perform a faster reliability assessment. Moreover, the estimated value of the activation energy indicates that mass transport controlled through grain boundary diffusion is crucial for Pb-rich coarsening under ageing treatment. For the research investigations, the BGA on the PCB model was simulated using the properties of the material in Table 4 for the SAC and lead-based eutectic solders for 45 days (64,800 mins). It could be observed that cracks/ruptures are taught to develop around the solder balls top and bottom flanges.

4.0 Results and Discussions

4.1 Isothermal Ageing of Solder Joint Interconnect

The schematics in Fig. 8 shows the simulated results obtained using the properties of the materials for the thermal ageing effect. A temperature of 40°C, 25°C, 75°C and 150°C was used for the FEA simulation studies. Also, from the results, it was discovered that creep deformation tends to occur at a significant rate when the homologous temperature is 0.4 or higher. From the homologous temperatures obtained from calculation, it was recognised that the lead-based eutectic solder alloy and lead-free SAC solders have higher homologous temperature for lead-based eutectic (0.50, 0.65, 0.76 & 0.93), SAC305 (0.46, 0.60, 0.71 & 0.86), SAC387 (0.46, 0.61, 0.71, & 0.86) and SAC396 (0.46, 0.60, 0.70 & 0.86). It is was discovered that creep occurs faster at higher temperatures. However, what constitutes a high temperature is different in different SAC solders. As stress increases, the rate of deformation increases. The results also show that strain develops at the centre and corner joint of the solder specimen at high temperature and then begins to drop gradually as the temperature decreases. The outermost solder joint always experiences the highest inelastic strain energy. Based on the result of this research, it was concluded that at low
temperatures, the thermally activated mechanisms of total deformation in the solder results in the strong strain rate effects, whereas at high temperatures they are limited.

4.2 Thermal Cycling of Solder Joint Interconnect

4.2.1 Equivalent stress simulation results for lead-based eutectic solder alloy and lead-free SAC solders subjected to a thermal cycling test

In electronic packages, thermal stresses have been known as the central problem, which can cause crack initiation and influence operational functionality. Because of the significant coefficient of thermal expansion (CTE) mismatch between constituent materials, an electronics package is subjected to thermal deformation under thermal-cycling conditions during its application. Specific study has been concentrated on solder joints in electronics packages as a result of the thermo-mechanical performances of solder joints is the basis to ensure the long-term reliability of electronic packages, not only because the solder joints provide the thermal and electrical interconnection, but moreover they are the sole mechanical attachment of the electronic components to the Printed Circuit Board (PCB). The constrained solder joints are cycled between the lowest and highest temperature limits depending on the environment of use, which result in most of the failures of microelectronic packages. Comparisons between the stress performances of lead-based eutectic 63Sn/37Pb and lead-free SAC387, SAC396 and SAC305 solders were conducted using ANSYS packages. The plot and schematic results are shown in Figure 8 – 12.

4.2.2 Strain rate of solder joint results subjected to a thermal cycling test

One of the meaningful achievements in this research is that solder joints failure is highly strained rate dependent. Strain energy is the energy stored in a body due to deformation. Solder alloys are usually applied in surface mount technology (SMT) as an interconnection material for thermal, electrical and mechanical connections to hold the component in position on the printed circuit board (PCB). Because solder joints are usually subjected to thermo-mechanical stresses at high operating temperature (0.5T_m to 0.8T_m) of the solder alloy, a significant quantity of deformation is introduced by creep during the strain cycle. At higher strain rate, solder joint failed at much on the BGAs. The study by Tsai et al. (2006) [41] investigated the high strain rate testing of solder interconnections. Their research shows that peak loads obtained from the impact tests are between 30% and 100% higher than those obtained from static shear tests for all combinations of solder alloy and pad finish.
The strain rate results of our study are presented in Fig. 14 – 17 showing areas with high strain rate along with the plot in Fig. 13 for the lead-based eutectic and SAC solders under thermal cycling tests. It could be observed that the strain rate represents the quasi-static regime, and the highest strain is near the BGA. The strain rate appears to be highest on SAC387 and lowest on the eutectic lead-based solder. It is expected that the solder joint is likely to fail under high strain rate load under different conditions including ageing time, strain rate and solder thickness. The time required for failure to happen is the rupture time. Either higher temperature or higher stress decreases the rupture time and increases the creep rate.

The extent of the creep described in this research can vary considerably depending on test conditions where the point on each curve depicts the crack. With increasing stress and temperature, the time to rupture and the extent typically decrease, whereas the total elongation increases.

4.2.2 Strain energy simulation results for lead-based eutectic and SAC Solders subjected to a thermal cycling test

The strain energy results are presented in Fig. 18 – 22 and tend to show a good relationship between the experimental (from literature) and simulated (numerical) strain energy. The results suggest that creep and strain continue to play a significant role in solder joint creep-fatigue even under conditions that would tend to be extended beyond typical low-cycle thermal cycling used in this work. Just like the creep deformation effects, similar results, it is observed that SAC387 have higher strain energy in comparison with the lowest strain energy results obtained for the lead-based eutectic solder. At higher power cycles, the strain energy-based model is capable of relatively accurate prediction with our dwell time of fewer than 15 minutes. This is true even for conditions that extended beyond low-cycle thermal cycling.
The schematic of the damage distribution and strain energy for eutectic and SAC solder is presented in Fig. 18. From the plot, we could deduce that the magnitude of the creep strain varies for different solder alloys. Dasgupta & Oyan (1991) [42] investigated a specimen solder to obtain the inelastic strain history during two different temperature cycles specified by UNISYS. As we have modelled the creep behaviour with Garofalo, the strain rate is assumed to have a power-law dependence on the stress magnitude. It is evident that when the temperature is large, the strain components increases and the maximum strain concentration with a move to the diagonal edges of the solder interface and fails due to creep cracks propagation and rupture. The element sizes vary from 0.01 to 0.005 and show the transformation from coarse mesh to very fine mesh until when two or three meshes have the same result. It is observed that the trend of the deformed areas of the solder joint damage concentrates at the top and bottom flange of the joint. These denote the region where increased reliability needs strengthening. This correlates well with the results by Libot et al. (2018) [43] who investigated the experimental strain energy density dissipated in SAC305 solder joints during different thermal cycling conditions using strain gauges measurements.

Ramachandran & Chiang (2017) [44] studied the feasibility evaluation of the creep model for failure assessment of solder joint reliability of wafer-level packaging. The simulation results of their research demonstrate that the maximum creep strain concentration happened in the corner of the solder joint near the chip pad side, which has a good agreement with the scanning electron microscope (SEM) image of solder joint crack location after failure from their simulated and experimental result. The Image of crack that was developed from the solder side near the silicon die at the point of the highest calculated strain observed. This shows that the stress/deformation occurs near the substrate as seen from the results of our simulation. Similarly, results obtained by Fu et al. (2017) [45] and Pierce et al. (2007) [46] shows comparable outcomes with high strain regions in the critical solder ball determined with FEM analysis and observation of the thermo-mechanical fatigue crack localised in the solder bulk on the component side.

5.0 Conclusions

This study investigated the creep damage of BGA solder interconnects subjected to thermal cycling, and isothermal ageing to advice on the most effective solder for achieving improvement in the thermo-mechanical reliability of solder joints of BGA soldered on PCB. The creep damage is presented in the form of stress, strain rate, total deformation rate and strain energy. It is discovered that the pattern of damage in the BGA solder bump occurs at the top and bottom of the bumped joint. Additional findings reveal that the solder bumped joints at the periphery of the BGA amass more damage. Nonetheless, the stress, strain rate, deformation rate and strain energy played an essential role in the strength and fracture behaviours of the solder joints. The SAC396 is found to possess the least stress, strain rate, deformation rate and strain energy damage than the lead-based eutectic solder. Based on the results of this study, it is recommended that the SAC396 is the most suitable replacement of the lead-free SAC solder in the drive for the most effective and reliable lead-free solder in the achievement of thermo-mechanical reliability of solder joints of BGA soldered on PCB. Isothermal ageing of solder joints, on the other hand, revealed a significant variation of the microstructure of solder joints, significantly affecting the properties of solder joints. The most notable changes were observed at the interface of SAC305 solder presented in comparison to lead-based eutectic solder, SAC396 and SAC387. The reliability of microelectronic components and assemblies can be considered as an expression of solder joints functionality.
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