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Impact of Crystalline Orientation of Lead-Free Solder Joints on Thermomechanical Response and Reliability of Ball Grid Array Components

E. Ben Romdhane, A. Guédon-Gracia, S. Pin, P. Roumanille, H. Frémont

Abstract – The microstructure of lead-free solder joints often consists of only one or a few randomly oriented tin grains as a result of cooling conditions and reactions that take place during the solidification. Due to severe anisotropy of the tin phase and this complex microstructure, the stress state of each joint will be unique, and lead to a dispersion in times to fail. This study aims at evaluating the impact of orientations of tin grains on the stress state of a BGA component. Different combinations of solder joint grain orientations are studied through thermo-mechanical simulations in order to assess the stress state of each joint. A significant effect of neighbouring joints has been observed for the different cases.

1. Introduction

Reliability of electronic equipment for automotive and aircraft applications is a major importance due to multiple environmental stresses (e.g. thermal, mechanical, thermo-mechanical). With the RoHS directive averting the use of lead (Pb), fatigue characterization of lead-free solder joint has widely interested industries and academics [1]. Although several researches study thermomechanical behaviour of solder joints on a macroscopic scale, few studies have considered the effect of the initial microstructure of SnAgCu solder alloy on the stress state of solder joints.

The microstructure of SAC solder joints after reflow is characterised by diverse tin grain morphologies with random crystalline orientations. Several studies have shown the complex microstructure observed in the initial state of SAC305 [2][3]. Due to this stochastic as-soldered microstructure and coupled with the highly anisotropic properties of the tin phase, the thermomechanical response o²f SAC solder joints greatly depends on the morphology and crystal orientation of its Sn grains [4]. For these reasons, early failures may occur unexpectedly and predicting the first failed joint is quite difficult [5][6]. Failures may be more or less randomly located and not always at the position of highest global strain or distance to neutral point [7][8]. The main goal is hence to predict the position of the first cracked joints using Finite Elements (FE) model that considers initial solder joint microstructure. Some authors already began to study the effect of anisotropy of coarse-grained joints by considering microstructure in their models [9]. Lovberg *et al.* investigated the anisotropic elasticity and position of a solder joint in a package modeled at assembly level and showed the influence of the grain orientations of neighbouring single grained joints on the stress/strain state on the corner joint [10][11] .

In this study, the influence of location and orientation of each single-grained solder joint in a BGA package is investigated by finite-element simulation. The goal is to provide a numerical tool making it possible to study the effect of initial microstructure on the stress state of each solder joint. In an ageing test campaign done in parallel, similar packages are submitted to different thermal aging and thermal cycling conditions. Microstructural analyses using electron backscatter diffraction (EBSD) as well as polarized light microscopy will be performed for comparison.

This paper presents the first steps of this approach:

1) an analytical parametric study to highlight the effect of initial microstructural characteristics of solder joints;

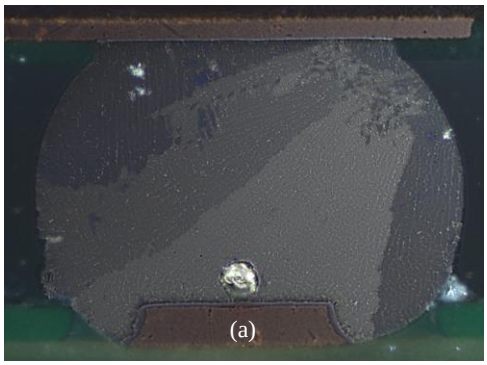
2) implementation of different combinations of crystalline orientations of solder joints in FE simulations to discuss the influence of orientations and location on the stress distribution of BGA solder joints

3) comparison with some published numerical and experimental data [10].

2. Microstructure of lead-free solder joints

2.1. Distributions of microstructure

The microstructure of a solder joint and its mechanical properties are very impacted by conditions and reactions that take place when SnAgCu solder alloy solidify. This microstructure has a truly random distribution with very varied morphologies. Several statistical studies showed that in typical SAC solder joints, the as-reflowed microstructure will consist of few large β-Sn grains and can be described as single-grained, cyclic twinned (also known as beach ball structure), twinned interlaced and mixed; The beach ball and interlaced microstructures are known to be both due to the sixfold twinning of tin, with three dominant grain orientations [12][13]. Examples of these microstructures are shown in **Figure 1**.



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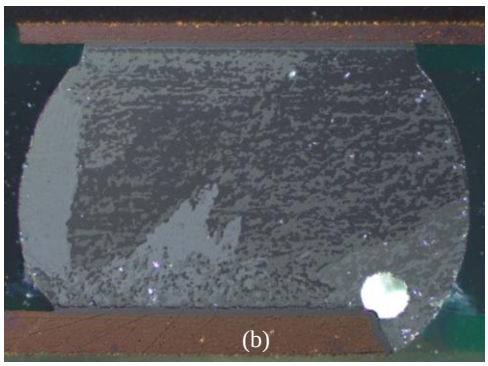


Figure 1. Polarized light observations of BGA solder joints microstructure: (a) beach ball structure, (b) interlaced grain

The occurrence of these morphologies in BGA components depends on solder volume, alloy composition, surface finish and cooling rate. 16% to 80% of solder joints are single-grained and their orientations tend to be more or less random [10]. Zhao *et al.* showed that there is a relation between the temperature gradient during solidification and the orientation of tin grains, where the c-axis tends to depart from the direction of temperature gradient by 45 to 88 degrees. However, these results are established on only four joints (10 grains in total) [14].

2.2. Failure Mechanism

When a lead-free solder joint is exposed to thermal cycling, recrystallization will happen in the high strain region near the solder pad. The recrystallization is characterized by the production of a large number of randomly orientated subgrains in the higher deformation areas. A network of high angle grain boundaries along the high strain region during thermal cycling is formed after a global recrystallization [15]. This network represents a high energy area that provide favourable intergranular crack propagation paths until failure [16][17]. Initially, recrystallization is slowed down due to precipitation hardening caused by intermetallic (IMC) particles but strain-enhanced coarsening will take place during thermal cycling. Despite recrystallization has been localized at twin boundaries and voids, it is most often favoured in the neck region due to the strain-enhanced precipitate coarsening that occurs fastest there. During thermal cycling, the spacing between inter-particles increases in the high strain area; the material softens which will further accelerate the coarsening of the precipitates. This coarsening will decrease the pinning effect of the secondary precipitates, allowing the formation and rotation of subgrains which will finally lead to high angle grain boundaries.

As the degree of coarsening and recrystallization is impacted by the strain level, the orientation of tin grains will strongly affect the damage evolution; an unfavourable orientation and position of a solder joint can cause early failures (**Figure 2**).

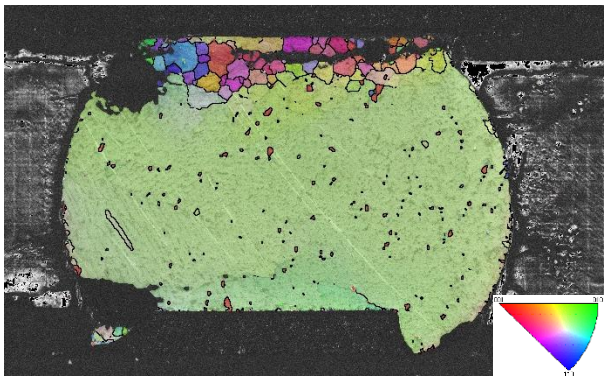


Figure 2. EBSD analysis (IPFy orientation map) of failed solder joint after thermal cycling, -55/125°C

2.3. Impact of microstructure on solder joint fatigue life

The reliability of solder joints is affected by Sn grain morphology and orientation. In Ref. [2], single-grained solder joints with certain orientations were observed to fail unexpectedly early, as compared to multi-grained SnAgCu solder joints.

The presence of an interlaced Sn grain morphology was correlated with a delay in crack initiation and the degree of interlaced tin grain morphology has an impact on the fatigue lifetime of solder joint. Arfaei *et al.* showed that the variation of lifetimes with changes in surface finish in LGA solder joints was directly related with these changes in Sn grain morphology for six different surface finishes (Figure 3) [12].

Solder joints with mixed cyclic and interlaced twin structures may be detrimental for the fatigue lifetime of solder joints. As the interlaced region is supposed to be stiffer, because of the larger undercooling resulting in a larger degree of precipitation hardening, it may induce a high stress level in the area that is not interlaced where the interparticle spacing is higher. If this area also has a critical orientation that maximizes the CTE mismatch to the component, very early failures may occur [18].

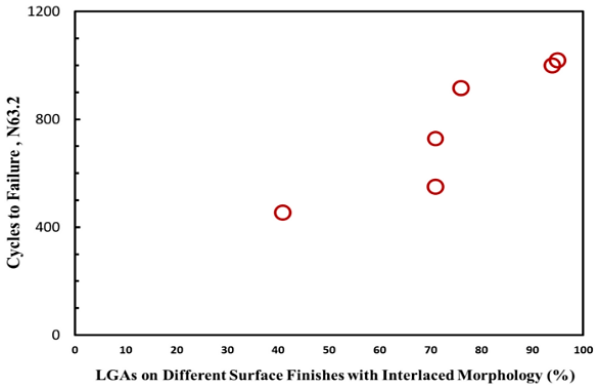


Figure 3. Plot showing the correlation between the lifetime of LGA samples and percentage of interlaced joints [12].

3. Analytical model

In order to verify the effect of crystal orientation of tin grains on thermomechanical response of each SAC solder joint, a first analytical approach is used.

For the theoretical analysis of a BGA assembly, Timoshenko proposed a theory that studies bending of bi-metal strip submitted to thermal loading [19]. Using this result, a simple analytical model permitted us to quickly calculate the shear stress in solder joints from dimensions and mechanical properties of the various elements of the assembly. To simplify the configuration, bumps are considered as beams with different Young's moduli so as to mimic various crystallographic orientations. Mechanical properties (α, E, ν) of moulding compound and PCB are first-order parameters to evaluate thermal-mechanical loading in solder joints. Dimensions and properties of the different elements of the package are described in Figure 4.

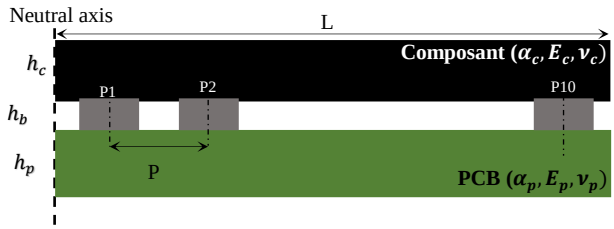
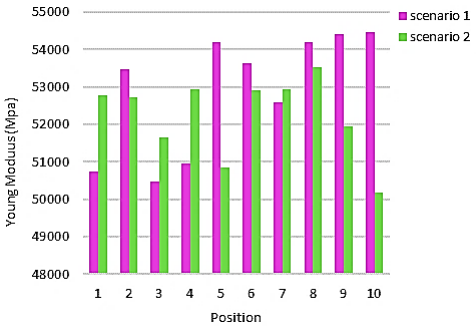


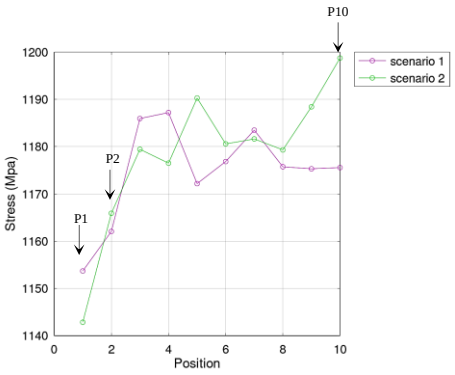
Figure 4. Simplified BGA assembly for the analytical model

The objective of this first analytic calculation is to assess the stress level during a temperature drop of 100 ° C of each bump for different Young's Modulus distributions, representative of variations related to the dispersion of bibliographic data and the orientation of the β-Sn phase.

A parametric study allowed us to set up multiple Young's Modulus distributions and to study the effect of changing Young's modulus of each bump along the length of the assembly. The different Young's Modulus are randomly generated. Fig. 5a shows an example for two Young's Modulus combinations randomly performed. The evolution of shear stress with position of joints for this two Young's Modulus combinations is presented in Fig. 5b. From these two scenarios, we can see that the most stressed solder joint is not necessarily located at the highest distance to neutral point (scenario 1). We can also see that the most stressed joint is not always the one with the highest Young's Modulus (the 4th joint in scenario 1) and each combination of Young's modulus gives a different stress state along length of the assembly. From these reasons, we can conclude that the stress state of each joint strongly depends on its orientation. So, to facilitate relevant and accurate lifetime predictions, modelling and simulation should be performed with many grain orientation combinations.



(a)



(b)

Figure 5. Random Young's modulus values as a function of joint position (a), shear stresses as a function of joint position (b)

This first analytical approach therefore let us suspect that the stresses experienced by a joint depend not only on its crystalline orientation, but also on that of its neighbours. On the other hand, the assumptions used in the models are too simplistic to conclude to quantitative results. So we started to take these parameters into account in finite element models.

4. Description of the finite element model

To generate a finite element model that allows implementation of different combinations of grain orientations, a model of a quarter Chip Array BGA with anisotropic properties is set up to simulate thermomechanical loads (Figure 6). A temperature drop from the reflow point (230°C) to the ambient (25°C) followed by one thermal cycle (-55/125°C) has been applied on the model.

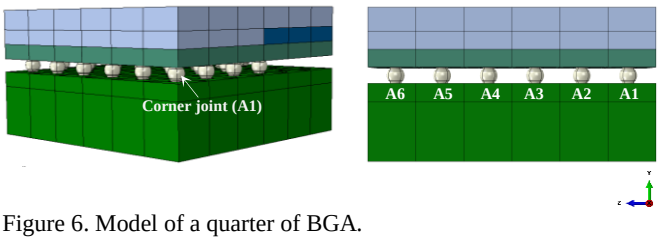


Figure 6. Model of a quarter of BGA.

The response of the lead-free solder joints to thermo-mechanical loading are very impacted by the anisotropy of the tin phase; Tin is one of the most anisotropic metals in the periodic table and is characterized by a body-centered tetragonal crystal structure with 4 additional atoms at four faces, as shown in Figure 7:

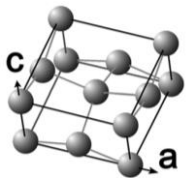


Figure 7. Unit cell of body centered tetragonal ß-Sn

Anisotropic properties of β-Sn were implemented in ABAQUS through its elastic coefficient matrix in stiffness form. This matrix is defined by 6 independent constants due to the tin crystal symmetry:

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \quad (1)$$

In order to change the orientation of the solder joints in the model, the elements of the joint are rotated using Euler angles. This rotation is done according to a first rotation φ around the z-axis, followed by θ around the new x-axis and finally Ψ around the updated z-axis and based on the rotation matrix:

$$R = \begin{pmatrix} c_3c_1 - s_3c_2s_1 & -c_3s_3 - s_3c_2c_1 & s_3s_2 \\ s_3c_1 + c_3c_2s_1 & -s_3s_1 + c_3c_2c_1 & -c_3s_2 \\ s_2s_1 & s_2c_1 & c_2 \end{pmatrix} \quad (2)$$

Where c_1, c_2, c_3 and s_1, s_2, s_3 are the cosine and sine of the rotation angles φ, θ and Ψ.
All other materials in the model are modelled as linear elastic.

5. Results and discussion

Several works have pointed out the importance of the c-axis orientation with respect to the board surface on the fatigue life of solder joints to area array packages. Bieler et al. [8] observed a clear dependence of the thermomechanical response of SAC solder joints on their Sn grain orientation. They showed that Sn crystal orientations with very high CTE values (c-axis orientation parallel to the substrate) generated a maximal CTE mismatch in shear at the joint interface, and also had maximal tensile stress states in the hot part of the thermal cycle. Thus, these orientations presented the worst cases and hence the best cases are characterized by orientations with low CTE values (c-axis orientation perpendicular to the substrates).

For these reasons, we have chosen in this study to model the two extreme orientations with another third orientation with a c-axis which makes a 45 degree angle to the board surface.

5.1. Influence of crystalline Orientation on the stress state of the corner joint

In order to assess the influence of orientations on the stress state of the corner joint, three different cases of grain orientation are modelled. In all three cases, all joints have the same orientation.

Figure 8 shows the stress state in the corner joint as a function of orientation. As supposed from analytical approach results, the stress state in the solder joints strongly depends on their orientations. Although the highest stressed area was in the neck of the joint for all orientations, we noted a variation of the maximum Von Mises stress between 5% and 15% depending on orientation. Tegehall *et al.* argued that the orientation has an impact on the behaviour of the corner joint and therefore on its degree of recrystallization [10]. As a consequence, the orientation of the solder joint plays a significant role in the time to recrystallization and subsequently in the fatigue life of the solder joints.

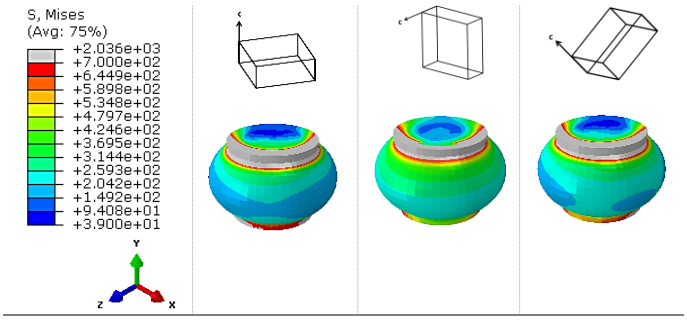


Figure 8. Von Mises stress in the corner joint as function of c-axis orientation

5.2. Effect of the orientation of the corner joint on the neighbouring balls

The objective from this part of the study, is to understand the impact of corner joint orientation on the stress state of neighbouring joints. We studied also three configurations but only by changing the orientation of the corner joint; the neighbouring bumps orientations are defined by a c-axis parallel to the substrate for each simulation. For the corner joint (A1), the three orientations chosen at the beginning of this section were implemented.

Results of two configurations are presented in Figure 9. Balls of the first range of the FE model were cut in half to show the representative stress state of each solder joint. As expected, we can observe that the corner joint with a c-axis orientation parallel to the substrate is more stressed than that with a c-axis orientation perpendicular to the substrate which validates that orientations with very high CTE value are more detrimental to the fatigue life than orientations with low CTE values.

This figure shows also that the stress state of their surrounding balls was impacted by the orientation of the corner joint. This effect is more remarkable on the stress distribution of

the joints A2 and A5 and depends on the value of the variation of the orientations from one bump to another.

These observations show that orientation has an important effect on the behaviour of the solder joints and therefore it influences their fatigue life.

5.3. Simulations of combinations of different orientations

To get closer to reality and have a more representative model, different cases of joint orientation combinations were modelled. Each case is characterized by a random c-axis orientations distribution; the crystal orientations implemented are also those defined at the beginning of this paragraph.

Simulations of three different combinations of bumps orientations are presented in Figure 10. As shown in this figure, by generating more realistic combinations, the effect of crystalline orientation on the behavior of the joints became clearer. Due to the combined effect of orientation of joint, its position and orientations of neighbouring bumps, the stress distribution of each solder joint is unique and locations of most stressed joints change from one combination to another.

On the other hand, by comparing the stress levels along the simulations carried out in this study, we observed that a model which contains joints with different orientations has a higher stress level (Figure 10) with differences of 37% compared to the stress level observed in the simplest cases (Figure 8) and 25% for configurations where the orientation of the corner joint has been modified (Figure 9).

These results explain the dispersion in times of failure and lead to the conclusion that fatigue life of an area array component will be strongly affected by the initial microstructure of solder joints. For that, it is necessary to make lifetime predictions based on a certain combination of joint orientations.

Since the initial microstructure has a significant role in the study of solder joints reliability, the fatigue life of an area array component can be also strongly affected by the morphology of joints. Further studies on the influence of grain morphologies on the stress state of BGA solder joints will be presented in a future publication.

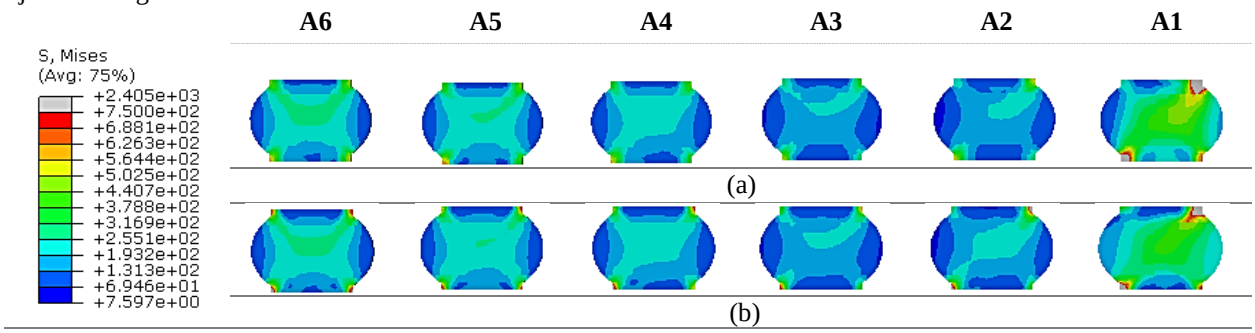


Figure 9. Effect of the c-axis orientation of the corner joint A1 on the neighbouring bumps; (a) A1 with a c-axis orientation parallel to the substrate, (b) A1 with a c-axis orientation perpendicular to the substrate

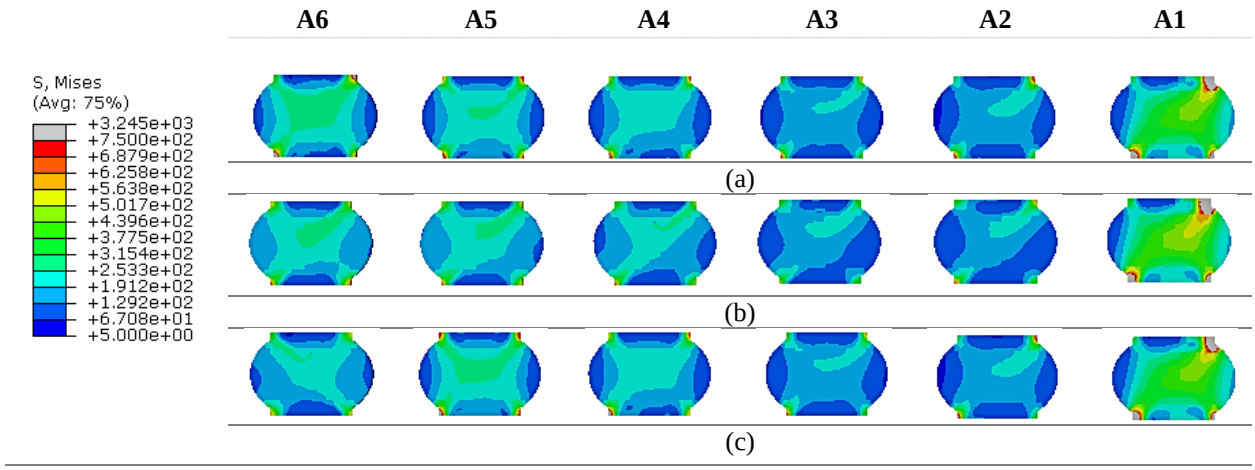


Figure 10. Stress distribution in each joint of the first range of the model of three different combinations of grain orientation

6. Conclusion

The investigations detailed in this study aim at giving numerical tools for designing solder joints reliability taking into account crystalline grain orientation. Simulations confirm that the stress state of each single-grained solder joint is unique and affected by the response of its neighbouring joints which gives a unique thermal fatigue behaviour for each combination of orientations. More realistic simulations are now possible in order to study the lifetime of the solder joints as a function of their initial microstructure.

This tool will be used in future work to run an important number of simulations with different sets of joint orientations; A sensitivity analysis based on Monte Carlo method will allow us to define multiple distributions of orientations. The results will be compiled into a response surface in order to define the most critical case. These response surfaces will also be useful for studying the distribution of predicted lifetime as a function of crystalline orientations and positions of solder joints.

This work is also supported by a statistical study of crystalline orientations of joints in the initial state; after cycling the influence of the crystal orientation of the tin grains on the failure mode of SAC305 solder joints will be evaluated. This also allows us to better understand the as-reflowed microstructure and its evolution during thermo-mechanical loading in order to improve the interpretations of the modelling results.

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