Impact of Solder-Joint Tilting on the Reliability of LED-based PCB Assemblies: A Combined Experimental and FEM Analysis

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Abstract

The impact of solder-joint tilting on the reliability of high-power LEDs soldered on PCBs is investigated by means of FEM simulations correlated with thermal cycling experiments. A non-uniform solder joint stand-off height is implemented into the FEM and, using crack propagation modelling approach, the number of cycles to complete fracture are predicted.

1. Introduction

High-power LEDs soldered on Printed Circuit Boards (PCBs), typically based on Insulated Metal Substrates (IMS), are quite often used for high-end applications. The solder connection provides a good heat removal pathway from the LED to the substrate.

Due to the Coefficient of Thermal Expansion (CTE) mismatch between LED package (e.g. ceramic) and PCB, a temperature exposure of the soldered assembly will lead to a different expansion (temperature increase) or compression (temperature decrease) for the LED package and the PCB. This leads to stress in the solder interconnection which translates into inelastic deformation. At low temperatures, this inelastic strain will be mainly plastic deformation while at high temperatures creep will be the dominant deformation mode.

It is well known that repeated inelastic straining of the solder joints lead to fatigue crack formation and propagation [1]. Switching on and off the LED results in a temperature cycle of the component and therefore stresses the solder joint each time and solder fracture is therefore a major potential cause of failure. High-end LED assemblies require a minimum lifetime which reflects into a minimum number of temperature cycles.

High-power LEDs can have pad geometries (i.e., footprints) which lead to tilting effect during the soldering phase (e.g. reflow). The ideal situation is a uniform stand-off height all over the solder pad. However, the LED can tilt resulting in a lower stand-off height at one side and a higher stand-off at the other side (**Error! Reference source not found.**), because of some unbalances during soldering phase enforced by the surface tension effects of the solder.

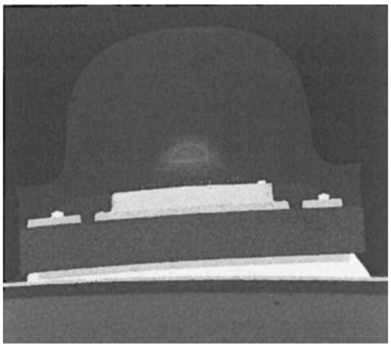

Fig. 1: Cross-section of a tilted LED solder assembly

This work investigates the impact of non-uniform stand-off height of the LED package on the lifetime of the LED-based PCB assembly. In order to evaluate this impact, thermo-mechanical FEM simulations were performed including crack propagations. This is needed as the solder plane is rather large and the crack propagation changes the stress/strain state depending on the location (and local stand-off height). In parallel, thermal cycling tests have been performed on soldered LED assemblies in order to measure how many cycles the soldered assembly can have up to failure. For each assembly, both the lifetime (i.e., number of cycles to electrically measured failure) and the tilt of the LED are registered.

2. FEM approach

Two extreme cases are considered in this simulation study: a perfect assembly with uniform solder joint stand-off and a maximally tilted LED resulting in one side with almost no solder anymore between the solderable pads. The other side has consequently double stand-off. The FEM for both cases are depicted in Fig. 2 and Fig. 3. The software code is Msc.Marc. Due to the non-uniform stand-off height, the mesh could only be reduced to half of the structure. The LED is reduced to the main part, namely the ceramic substrate.

An ANAND based model is selected to perform the visco-plastic behaviour of the lead-free solder [2]. An accelerated temperature cycle is applied as boundary condition. The main stress is induced by the CTE mismatch between the LED package (4.5 ppm/°C) and the aluminum substrate (23 ppm/°C) of the Al-base IMS; the IMS layers also function as stress buffer.

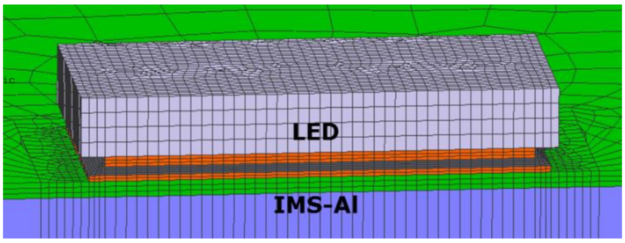

Fig. 2: Finite Element mesh of non-tilted assembly with uniform stand-off height

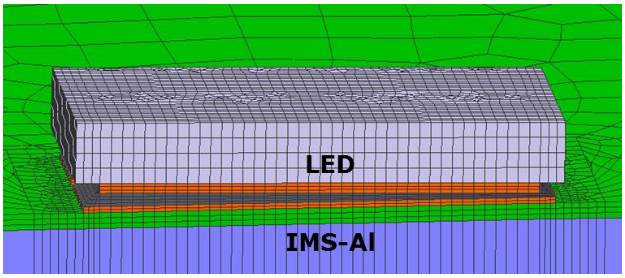

Fig. 3: Finite Element mesh of maximally tilted solder assembly with almost zero stand-off height at one side, double stand-off at the other side

The result of interest is the creep strain induced during one temperature cycle. The creep strain is linked to a crack growth model (Fig. 4) which will be used to predict the lifetime, expressed as the number of temperature cycles [3].

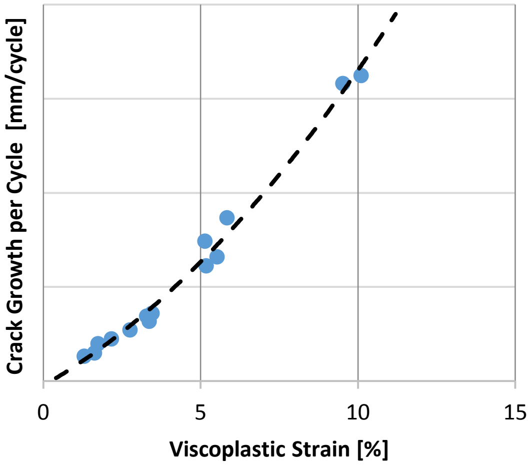

Fig. 4: Empirical model translating the simulated creep strain in a crack growth per cycle.

3. FEM results and creep strain based lifetime prediction

Fig. 5 and Fig. 6 show the creep strain distributions in the solder areas or the two cases. For the **non-tilted** assembly, the maximum creep strains are found in the four corners. It is therefore expected that cracks will start from the four corners with the same growth per cycle. For the **maximally tilted** assembly, the highest strains are found in the two corners with almost zero stand-off height. The creep strains are about 3 times higher compared to the non-tilted assembly.

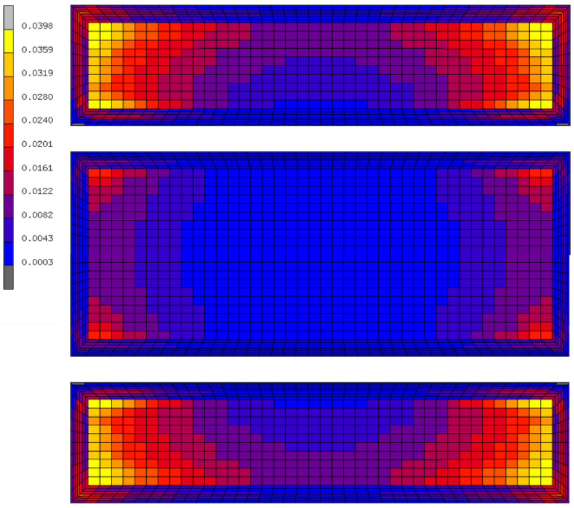

Fig. 5: Induced creep strain per temperature cycle in the ***non-tilted*** *soldered assembly*

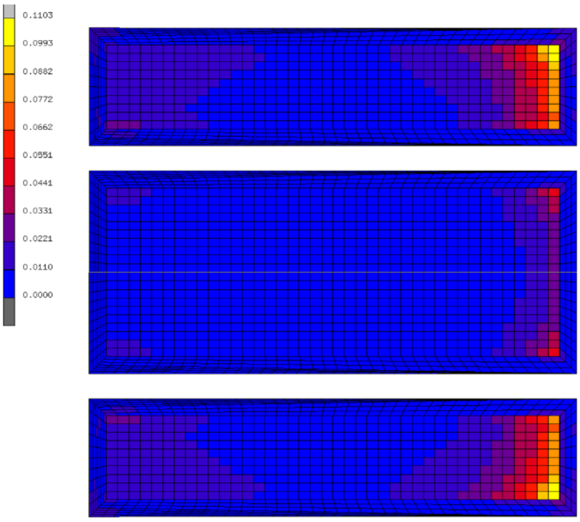

Fig. 6: Induced creep strain per temperature cycle in the ***maximally tilted*** *solder assembly*

Making predictions on these creep strains in the maximum areas would reflect that the life time of the tilted assembly would be few times lower than the non-tilted assembly. However, it is expected that once the crack grows, the stand-off is increasing so the local strain will reduce. Therefore, it is highly advised to include also the crack propagation in the model.

4. Crack propagation modelling

In the advanced software codes, crack propagation features such cohesive elements and XFEM are available which are able to have a growing crack in the mesh structure. This is however a very time consuming approach. One temperature cycle simulation easily takes several hours, so a full crack growth simulation lasting over thousands of cycles would take weeks, even months.

Therefore, a “pragmatic” approach is followed to calculate the number of cycles needed to propagate a full crack. The creep strains are calculated at different stages of the crack propagation. The crack is formed by deleting a layer of elements, as depicted in Fig. 7.

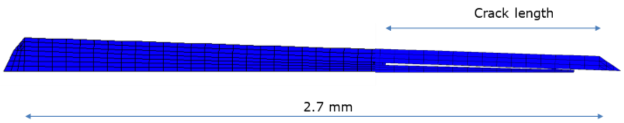

Fig. 7: Definition of crack length implemented in the model by removing one horizontal layer of elements

Fig. 8 shows the creep strain distribution in the solder joint at different stages of the crack propagation. The highest strain values are found once the crack is formed. When the crack is further growing, the creep strains are reducing and this is thanks to the lower DNP (Distance to Neutral Point) which is reducing the loading.

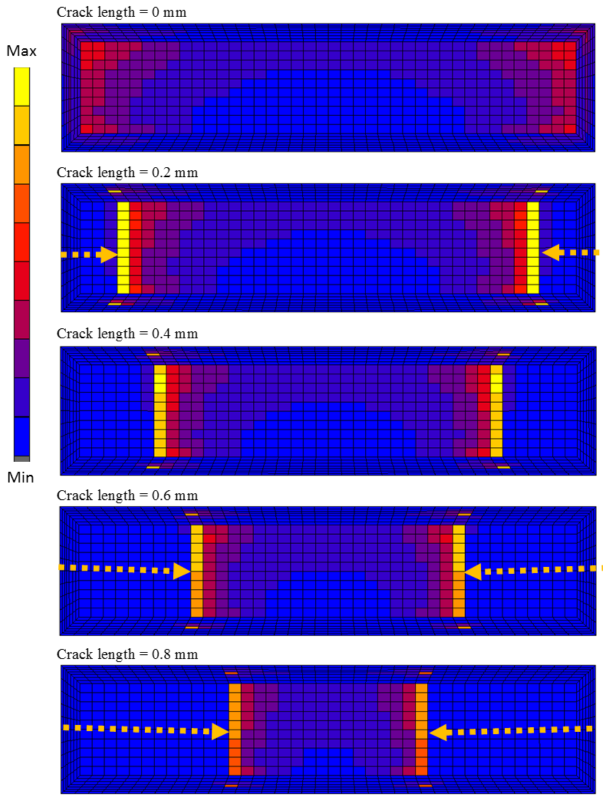

*Fig. 8: Evolution of creep distribution at different stages of a propagating crack for the **non-tilted** case.*

Fig. 9 shows the evolution of the creep strain distribution during the crack propagation. The values are the average of a damage volume taken in the area of maximum strain.

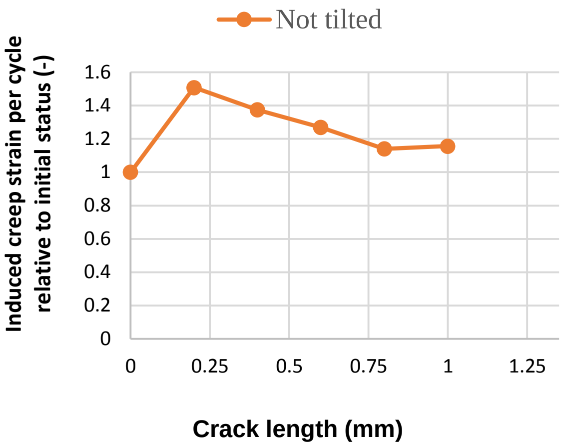

*Fig. 9: Maximum creep strain evolution during an evolving crack (**non-tilted** case).*

Similarly, the creep strain distributions are shown for the tilted version, with a crack growing from the thinnest side (Fig. 10). A peak is found for a crack length of 0.6 mm.

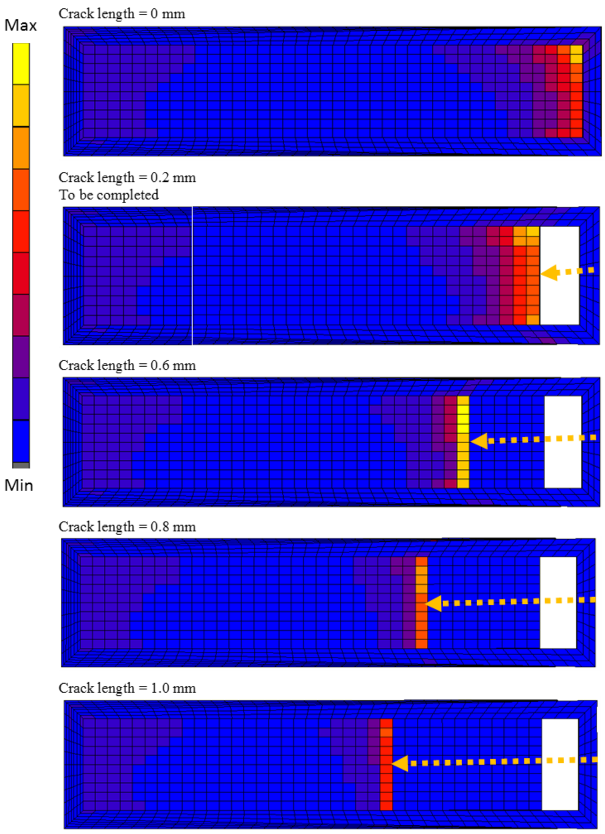

*Fig. 10: Evolution of creep distribution at different stages of a propagating crack for the **maximally tilted** case*

Fig. 11 shows the evolution of the creep strain distribution during the crack propagation. The values are the average of a damage volume taken in the area of maximum strain. These values are much higher at the thin side compared to the non-tilted case. However, at the thick side, the strain values are much lower.

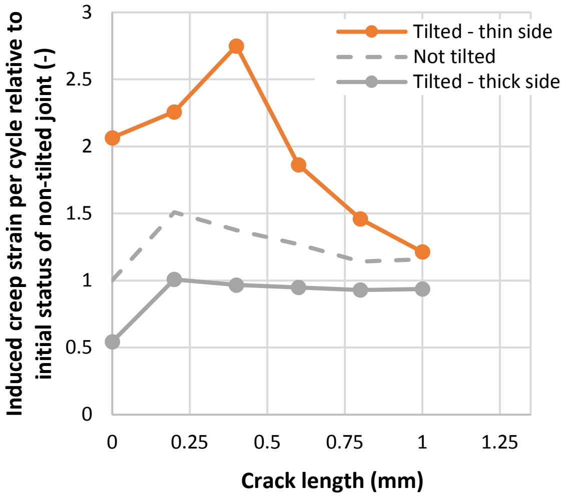

*Fig. 11: Maximum creep strain evolution during an evolving crack (**tilted** case).*

The empirical crack growth model, shown in Fig. 4, is now used to translate the curves of Fig. 9 and Fig. 11 into a growth of crack area. As the solder land is 2.7 mm in total, a complete fracture is defined when both crack fronts reach each other.

Fig. 12 shows the crack propagation starting from both sides of the solder pad. This is done for both non-tilted and tilted LED assembly. For the tilted assembly, the crack grows quite fast from the thinnest side but very slowly from the thickest side. On the other hand, the crack propagates in the same manner from both sides for the non-tilted assembly. Surprisingly, both cases end up at about the same number of cycles to complete fracture.

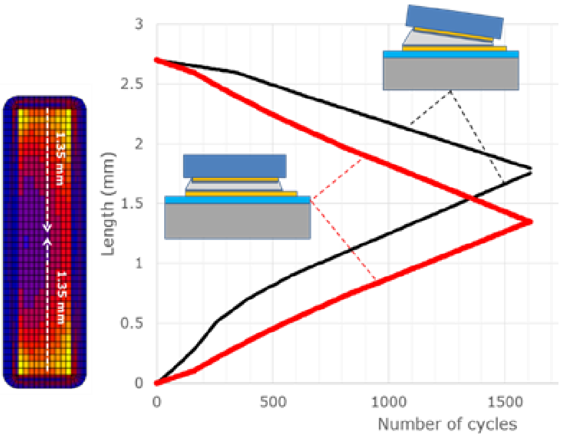

Fig. 12: Crack propagation modelling for tilted and non-tilted assemblies

6. Thermal cycling experiments

Temperature cycling experiments were performed on more than 100 soldered LED samples with the same thermal cycling conditions used for FEM simulations. On these samples, the tilting angle was also measured. In order to see if there is a correlation between tilting and time to failure, the cycles to failure is plotted versus the tilting angle for each sample (Fig. 13). The graph clearly shows that there is no statistical correlation, confirming the simulation. Hence, tilting of the LED has no major impact on the final lifetime.

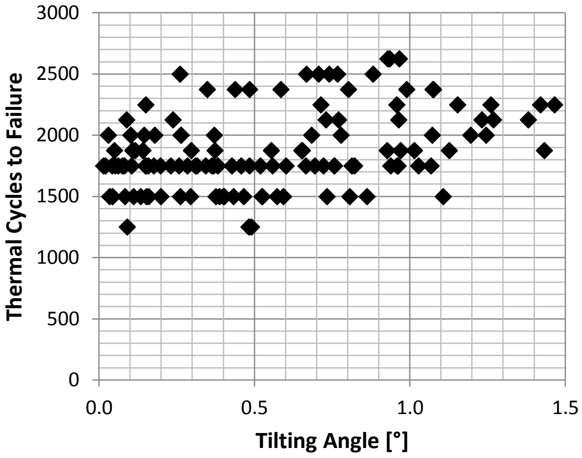

Fig. 13: Correlation graph showing for each sample the number of cycles to failure versus the measured tilted angle

6. Conclusions

The conclusion from the modelling is that there is almost no difference in the expected lifetime between tilted and non-tilted assemblies when the failure is defined as completely propagated solder-joint crack on LED pads. This result is confirmed by thermal cycling experiments.

References

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