Thermal Lap Shear Tests on MEMS Interconnect Solder joints

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1. Introduction

In recent years, solder joints have been continuously incorporated in electronics packages and MEMS-technology, too. The strong trend towards high-temperature applications can be observed in combination with the tendency to increasingly use of lead-free solders. Low deformation and stress distributions between the different interconnect components coupled with long-term reliability becomes a hot issue. A key factor of solder joint failure is the mismatch in the thermal expansion coefficient between the different individual components in various applications among them automotive, telecommunication or wide range of MEMS. Fatigue tests are directed in two main directions (i) thermal induced low cycle fatigue /1-4/ and (ii) mechanical loading such as vibrations and shocks /5/ as well.

The combination of Finite-Element-Analysis (FEA) and advanced experimental testing methods are a suitable way to describe time and temperature dependent strength, fatigue and interface behaviour including the formulation of material laws of solders and adhesives, too. Measured deformation fields and material parameters are essential assumptions to predict the reliability and to predict the lifetime of multi-material structures and MEMS packaging.

2. Thermal lap shear device - TLSD

The authors have developed a new experimental technique, Fig. 1, to carry out advanced investigations of thermo-mechanical reliability of material compounds for applications in MEMS packaging and optical interconnection technology with a special focus on thermal cycling tests. The use of adapted materials with optimised thermal parameters like CTE enables the implementation of true-to-life loading conditions of the materials under test.

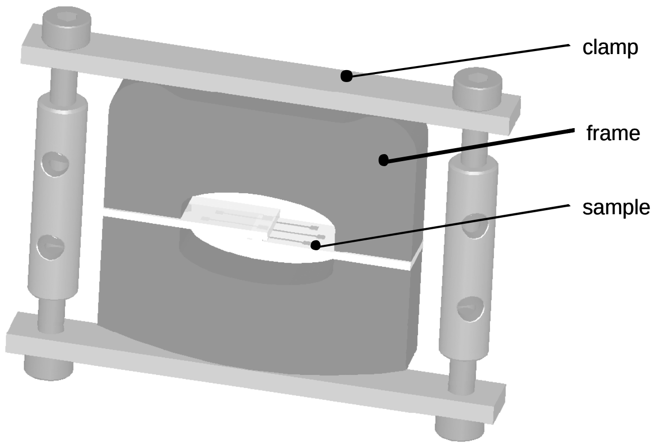


Fig. 1 TLSD-module for static or cycling thermal loading of a lap shear specimen

The test specimen may be a single or double lap shear specimen made from one material containing an arbitrary shaped joint. The interconnect can be made forming a layer, a cluster of bumps, or a similar array. The shear specimen is fixed by two clamps made of another material than the substrates of the specimen. The clamps are simply braced by a loading frame.

Due to the adapted substrate geometry the developed methodology is favoured by various characteristics:

- Shear dominated loading causes frequently the dominating failure mode in packaging and interconnection technology.

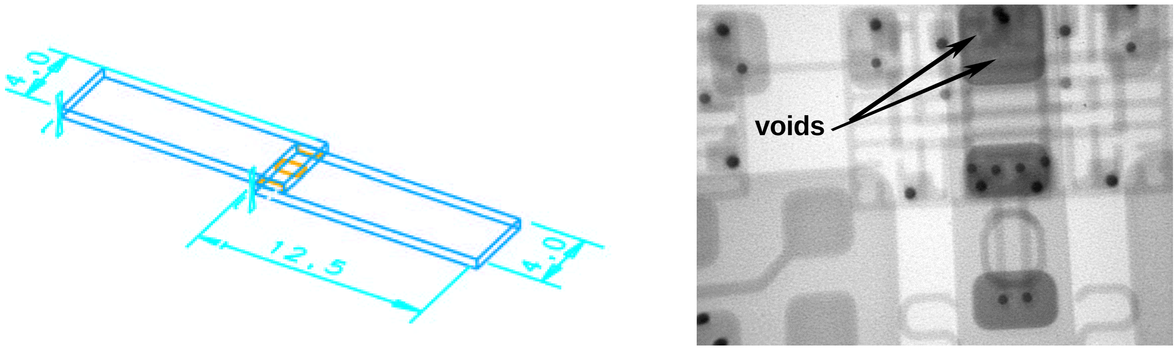
- Thermally induced loading is most realistic in various cases of interest.
- Loading can be varied by choice of the clamp size, the joint thickness, and the materials used for the shear specimen substrates or clamps, respectively. The latter determines the CTE mismatch between specimen and clamps.
- A mode mixture of the stress state in the joint is realistic for many applications. It can be affected by the choice of the substrate thickness or of the joint shape (e.g. layered joint versus array structure) among others.
- Static and cyclic thermal loading can be investigated by the same device. Unfortunately, a force measurement is presently not available.
- The same lap shear specimen can be used for different testing equipment, e.g. mechanical testing machines.
- Local deformations can be measured at the lap-shear joint applying optical techniques.

To study real deformations at interconnections the samples can be thermally loaded in different manner. The determination of both global and local displacement distributions allows the description of the strain state on the exposed surface. The strain fields derived from the displacement components enable the analysis of selected stress or damage stages of fatigue. The cyclic accumulated creep strain or dissipated strain energy density, applied in a Manson-Coffin law, are known as appropriate failure criteria. However, the critical parameters used in the Manson-Coffin law are not very well known. Only a few data are particularly available for the lead free solders. The thermal lap shear test shortly described above has the potential to address the following issues:

- All results are obtained for real solder interconnects. The joint data can be compared to bulk data already known.
- Microscopic in-situ monitoring of the deformation at the surface of the lap shear joint is suitable to investigate changes in the microstructure and of the solder degradation, respectively, at selected stages of the cycling history.
- Solder fatigue failure and related Manson-Coffin parameters can be detected. Solder constitutive assumptions, i.e. solder creep, can be verified for different solder materials.
- Optical deformation measurements can be performed by microDAC technique in-situ.

3. In-situ deformation analysis of solder interconnects

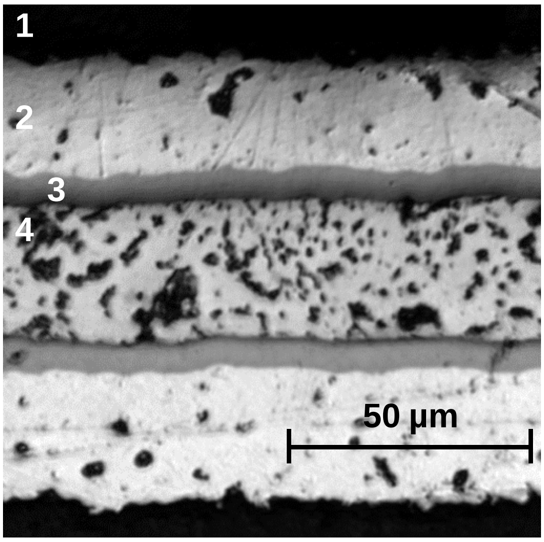
PbSn- and SnAgCu-specimens have been manufactured in LTCC thick film technique, Fig. 2. The current test device obeys a low cyclic creep strain with maximum values in the range of approx. 1%. Two different temperature loadings can be performed, one for thermal cycling and the other one for in-situ monitoring of solder degradation and local deformation measurement in the same TLS-device. Considering real temperature profiles of electronic devices they were cyclic loaded between 5 °C and 85 °C in a shock chamber.



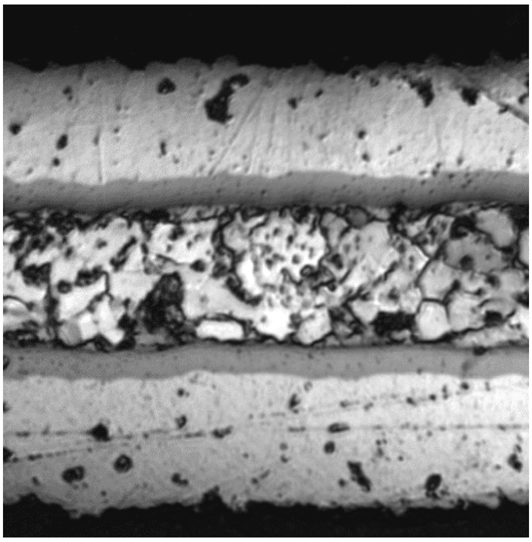
(a) (b)

Fig. 2 Specimen geometry including the solder pads (a) and X-ray picture containing only a few small voids; solder thickness approx. 40 µm

Thermal induced deformation states have been in-situ recorded by laser scanning microscopy after 110 thermal cycles between 5 °C and 85 °C. Fig. 3 shows temperature dependent local degradation effects in the solder structure. A structure coarse-graining as well as a formation of grain size can be observed.



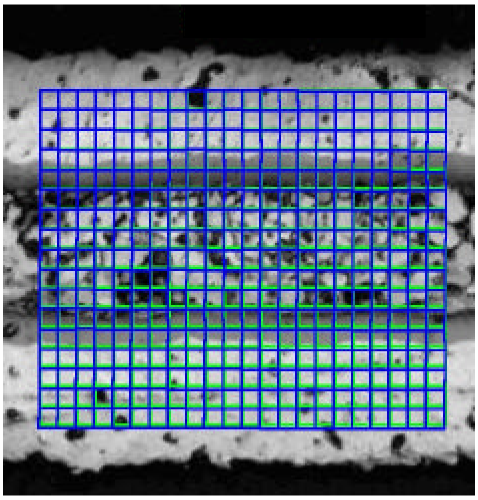
a) at 30 °C



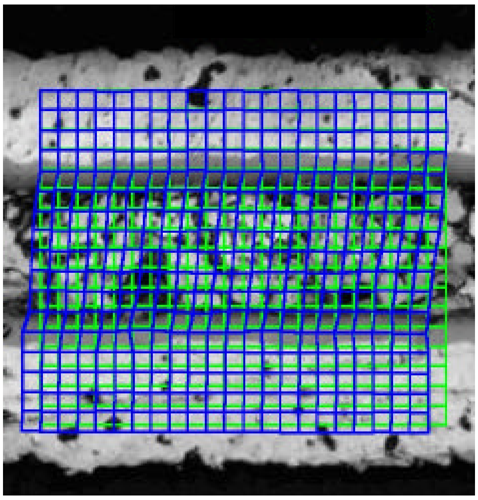
b) at 150 °C

***Fig.* 3** Structure of solder PbSn (polished after temperature cycling) after 110 thermal shock cycles between 5 °C and 85 °C at two different temperatures
(1 … LTCC substrate, 2 … thick film layer, 3 … diffusion barrier, 4 … solder ≈ 40 µm thick)

The application of the non-destructive measuring techniques /6-7/ among them microDAC (Deformation Analysis by means of Correlation) allows the measurement of global and especially of local deformation behaviour in the solder /8-9/. Displacement fields up to the submicron range can be analysed. This method is based on displacement field computing from a sequence of digitised micrographs recorded from continuously loaded specimens, Fig. 4. Cross-correlation algorithms are used to extract the incremental in-plane displacement fields by comparing two loaded state images. During the last years, the technique has successfully been applied to measure both homogeneous and inhomogeneous deformations on specimens and components investigated in different kinds of microscopes.



T^{neat} = 90 °C



T^{neat} = 150 °C

Fig. 4 Displacement fields of eutectic PbSn-solder recorded at different temperatures during the 1st heating run after 110 thermal cycles between 5 °C and 85 °C

The images of the solder layer are in-situ recorded at selected temperature rise by means of a laser scanning microscope (LSM) in the example presented in Fig. 4. The analysis grid is coloured green. The image field is located at a certain distance to the edge of the layer to avoid influences of the edge effects. To minimise measuring effects a limited number of measured values is summarised to an average value. Only very small deformations have to be measured with a sufficient accuracy.

The in-situ recording of the load-dependent changes in the surface region of the materials also allows the evaluation of the local material behaviour in the solder layer. Fig. 5 shows the curves of the u_x-displacement component measured for selected temperature rises having the same history. The displacements in the lead-free solder are nearly two times smaller than in the eutectic PbSn. Presently, systematic tests are carried out to check the reproducibility and accuracy.

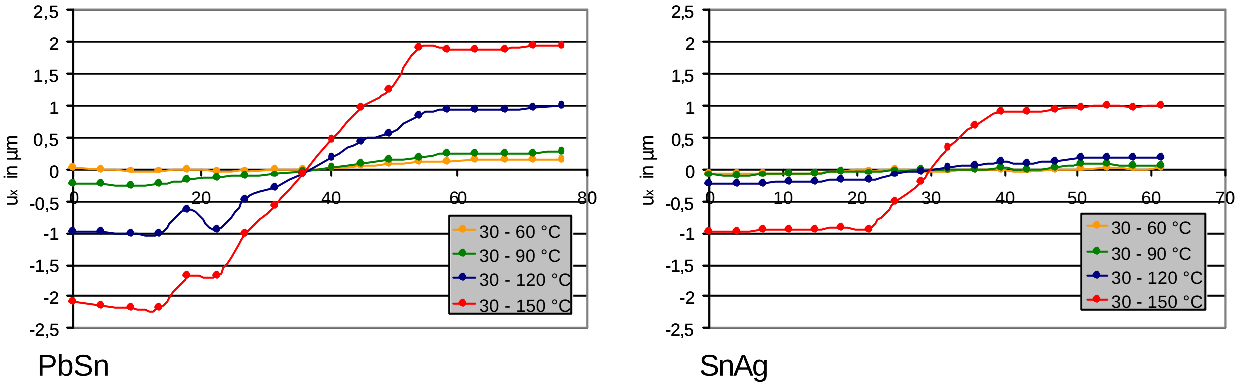


Fig. 5 u_x(y)-displacement curves for different temperature rise in the 1st heating run after temperature cycling

4. FE-analysis

Parallel to the experimental investigations both 2d- and 3d-FE-modells have been generated to calculate numerically the deformation and stress distribution in the solder /8/. Both a generalised plane strain model and a 3d-model are applied considering geometric dimensions measured from cross sections. A variety of FE-calculations have been performed to compare different solders stress distributions, creep laws and modelling details for the cycle 85 °C to 5 °C.

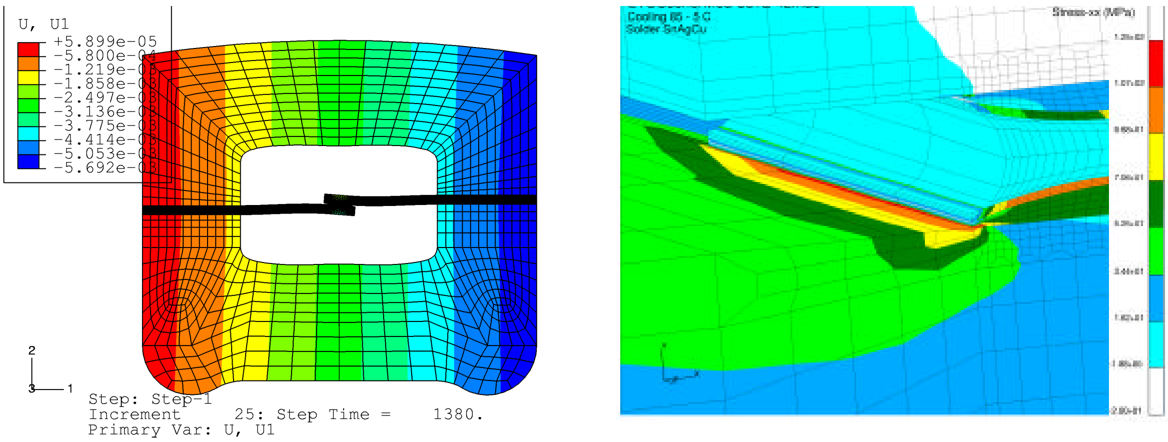
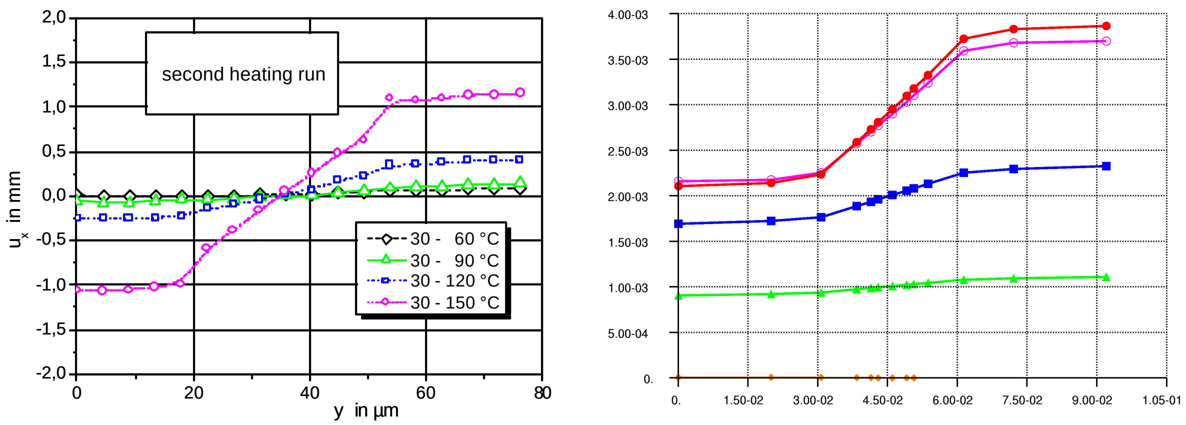


Fig. 6 u_1-displacment component (20x magnified) and stress concentration located nearby the edge of the metallisation of solder SnAgCu with $\sigma_{xx} \approx 122$ MPa

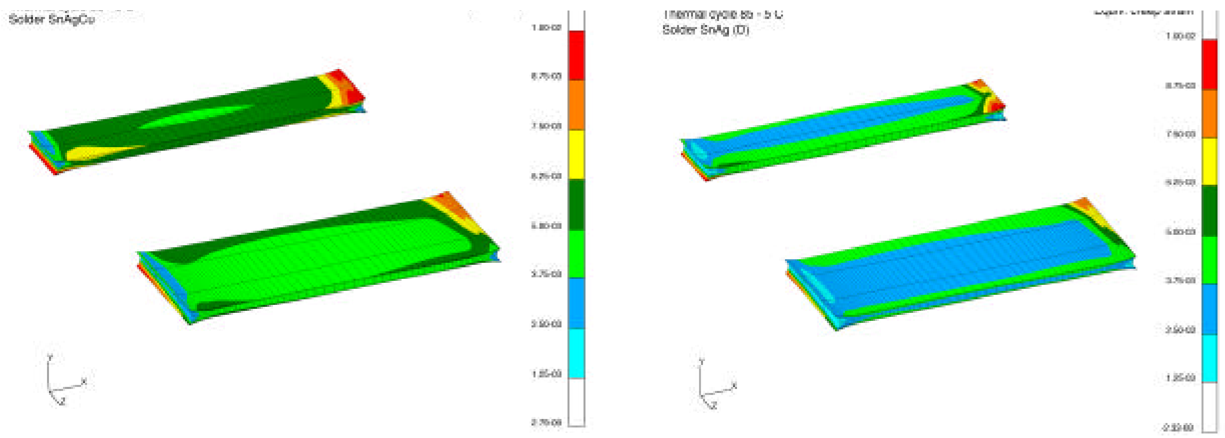
Fig. 6 shows the overall deformation behaviour. The specimens are not only sheared but additionally bended in vicinity of the joint. The stress maximum is located in the metallisation layer nearby the edges. A comparable uniform stress distribution can be observed in the middle interconnect region. Local values up to $\sigma_{xx} \approx 145$ MPa are estimated in the case of PbSn. Higher temperature cycle can lead to critical stress, which occurs primarily at the solder pad-ceramics interface edge.



measured by microDAC calculated by FEA

Fig. 7 Comparison of measured and calculated displacements in the PbSn-solder heating up from 30 °C to 150 °C (Second red line describes changed clamping conditions.)

A first comparison between measured and calculated displacements shows that the curves agree qualitatively, Fig. 7. Differences in the u_x-displacement have been observed for different heating runs after thermal cycling. This sophisticated phenomena is presently under investigation. The current test set-up version with a ΔCTE of 2.3 ppm obeys a low cyclic strain with maximum values in the range of 1 %, Fig. 8, and an even lower mean creep strain value in the solder layer dependent on the creep law applied /9/.



0.49 – 0.51 % for SnAgCu 0.37 – 0.42 % for SnAg

Fig. 8 Calculated cyclic equivalent creep strain of different kinds of solder

5. Conclusions

A new lap shear device is introduced to investigate thermally loaded solder materials under application specific conditions. Its compact design allows both static and cyclic thermal loading positioning the specimen in the same device. Their small dimensions enable an in-situ monitoring of temperature dependent solder degradation and of microDAC based local displacement field measurements using microscopic techniques. Very small displacement distributions in the range of 0.2 µm could be measured with a well-suited accuracy for different solders.

In parallel to the experiments FE-calculations have been carried out to check the quality of the TLS-device developed on one side. On the other hand, generalised plane strain models and

3d-models are compared for describing the strain and stress behaviour. A variety of calculations has been performed to compare the various solders and to check the creep laws available.

A good qualitative agreement is obtained for measured and simulated solder deformation depending on the temperature rise. Improved specimens as well as verified constitutive equations are presently tested to reduce the differences between experimental investigations and FE-analysis and to increase the accuracy.

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