A Novel In-situ Force Measurement Method for Real Solder Joints Fatigue

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ABSTRACT

The paper presents a novel approach to measure shear forces at solder joints during temperature cycle loadings. Due to plastic deformation inside the solder joints during the temperature cycles the solder-material-matrix continuously damages until micro cracks occur. This degradation behaviour is tracked by direct force measurement under thermal cycling loads using an Aluminum-Copper-loading frame. After the overall characterization of the fatigue machine by experiment and FE-Simulation, first successful results were generated based on 400µm solder balls on micro CSP-package stressed under -40°C and +125°C conditions. A force drop down to approx. 60% of initial force at the first cycles was measured. The measured forces kept in a steady state ranged over approx. 80% of lifetime until the material mechanically failed.

Keywords: LCF, solder joints, solder fatigue evaluation, in situ force measurements

1 MOTIVATION

In near future more and more 3D-integrted electronic devices will be developed. The heterogeneous implementation of sensor, RF-, HF-functions, processor and memory elements in one electronic package require very complex understanding of the materials' behavior. Further, the decreasing cycle times of development demand more application of simulation tools. The numerical simulations require material data, which describe the physical material behavior precisely.

In the past many experiments were performed to measure solder mechanical data. Solder joints, consisting of high-Sn-alloys (SnAg3.5, SnAg3Cu0.5, …), predominantly deform by high temperature plasticity. The mechanical data to be measured is the time- and temperature dependent creep behavior [4,6,7].

Obviously the most missing data on solder joints are trustable fatigue data and fatigue describing material laws. Many investigations were done and still are going on to determine fatigue data of solder joints. But the method of determination usually is reduced to thermal cycle tests of electronic devises assembled on substrates as Printed Circuit Boards (PCB). Either the loading conditions are roughly estimated analytically by calculation of total strain or numerical calculations are performed by respect of real creep behavior [1, 2]. Both methods came along with the disadvantage of missing information about the applied forces at joints.

$$\Delta\varepsilon_{total} = \frac{1}{\sqrt{3}\cdot h}\cdot\Delta\alpha\cdot\Delta T \qquad (1)$$

h..stand off, Δα..CTE difference, ΔT..temperature diff.

If the force loading condition at the solder joint during thermal cycling can be exactly measured the solder degradation process can be tracked from the first cycle up to the cycle of failure.

2 EXPERIMENTAL SET UP

The loading frame is a thermal controlled deformation machine, which allows inducting shear force load on joints. It consists of three symmetrical constructed main columns (or cores), which are connected by two aluminium arms. Inside the aluminium arms there are two flexure-hinges, which can be used as force sensors (see Fig. 1). The flexural regions are equipped by strain gauges to measure the total arm deformation.

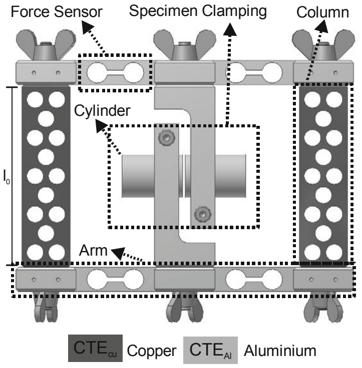

Fig. 1 CAD of loading frame for shear force measurement during thermal cycle tests

The outer columns' material is copper and the inner one is aluminium. The copper columns have holes inside to reduce their thermal mass.

The specimen is located in the lap shear shaped gap in the centre of the inner column because the inner aluminium column is divided and offers the opportunity to clamp two aluminium cylinders on a level with each other that the base areas of the cylinders are coplanar.

The base areas of the cylinders are adjusted arbitrarily towards each other. One of these is connected with the upper arm while the other is connected with the lower. The measured force sensor characteristic is shown in Fig. 2. The voltage over applied forces shows very high linearity, due to linear deformation behaviour of aluminium.

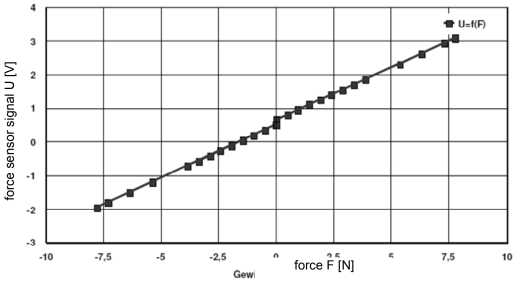

Fig. 2 Force sensor characteristic line, Voltage at strain gauges vs. applied force

The column length l_0 is essential to adjust the length differences Δl between the inner aluminium and the outer copper columns. The thermal strain differences of copper and aluminium during thermal cycle leads to deformation of the force sensor Δu_{sens} and solder joints Δu_{solder}.

$$\Delta l_1 = \Delta u_{Sens} + \Delta u_{solder} \tag{1}$$

$$\Delta l_1 = F/k + \Delta u_{solder} \tag{2}$$

$$\Delta l_2 = l_0 * \Delta T * (CTE_{Cu} - CTE_{Al}) \tag{3}$$

with $\Delta l_1 = \Delta l_2$

$$\Delta u_{solder} = (l_0 * \Delta T * (CTE_{Cu} - CTE_{Al})) - F/k \tag{4}$$

The aspired general deformation behaviour of the loading frame is linearity. Therefore, very good separations of the strong non-linear behaviour of solder can be achieved. This helps to reduce the risk of evaluation errors.

Material	**chemical composition**	**CTE**	**E-Module (20°C)**	**Poisson (20°C)**
AL 2017 T451	AlCu4MgSi	$22.9\ 10^{-6}\ K^{-1}$	72.5 MPa	0.33
Cu CW107C	CuFe2P	$17.1\ 10^{-6}\ K^{-1}$	120.0 MPa	0.35

Tab. 1 materials of loading frame

More detailed information about the electrical measurement of force signal, the specimen preparation and test chamber and electrical measurement condition includes different author's paper [5].

3 FEM – MODEL OF LOADING FRAME

The experimental setup was reproduced by virtual Finite Element Analysis software (ANSYS™). The numerical calculations are applied for:

- Better understanding of the experimental set up and hindering of mistakes
- Control of creep measurement data
- Extract material data from the experimental results
- Determine strain related fatigue data for simplified Coffin-Manson-Law

Fig. 3 shows the FE-mesh of one type of the loading frame. The mesh density differs in dependence of the model details. The specimen and the solder joints are meshed very detailed (see Fig. 4). The aluminum and copper columns come along with lower mesh densities, because the elastic deformation is expected to be very low and the thermal strain dominates. Only the active sensor region is meshed by increased mesh density, since its deformation must be calculated as accurate as possible to represent the reality. The sensor stiffness k calibration was done.

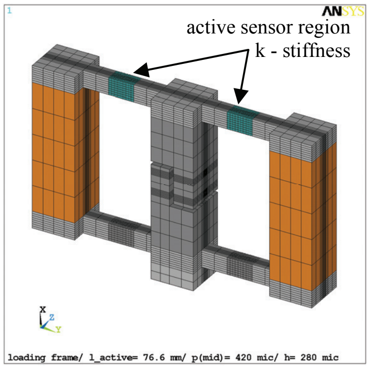

Fig. 3 FE - mesh of loading frame

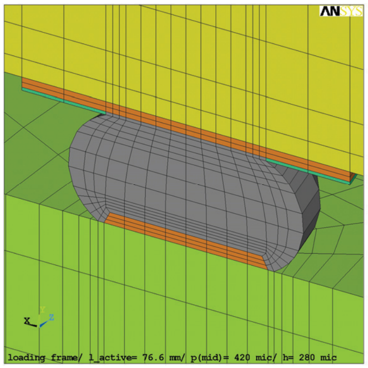

Fig. 4 FE - Mesh of solder ball at electronic device specimen interior of loading frame

4 CALIBRATION OF LOADING FRAME FEM MODEL

Before the FEM-Model can be used for solder material extraction the calibration of the model has been performed. Therefore the specimen region of the real loading frame was stiffed by simply connect the aluminum columns parts by Al-cylinder. So no specimen influenced the force measurement.

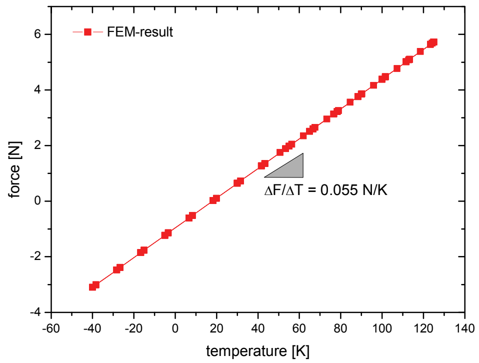

Fig. 5 FEM-result of force application as function of temperature in side the loading frame, specimen region was stiffed

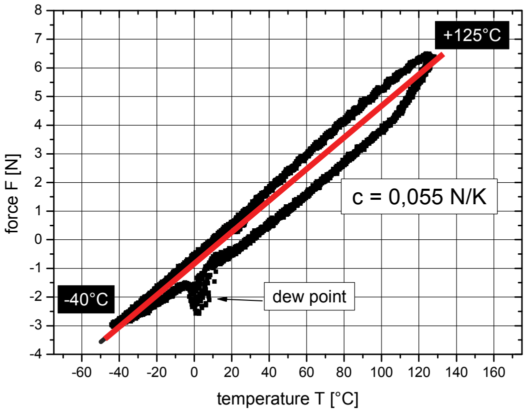

Fig. 6 experimental characterization of loading frame by stiffening specimen region

Fig. 5 shows final deformation behavior of the force sensor as function of temperature. Its slope turns out to be very linear. Over several iterations the sensitivity of the sensor has been adjusted to the real sensor behavior (see Fig. 6). The average slope of the measured results is equal to the FEM-results. But, in reality the sensor shows a hysteresis behavior. It may result from the time delay of the warming of the loading frame during thermal cycles. Additionally it is obvious, the dew of chamber humidity occurs at approx. 0°C. The signal influence comes from the moisture deposition on top of the sensor surface. Further developments must avoid this effect. But still, the FEM-calibration was successfully performed.

Further the simply thermal strain deformation of the copper and aluminum columns were checked. The resulting coefficient of thermal expansion for copper and aluminum fits well. Again the FEM-model behaves very similar to the experimental set up. The FEM model is calibrated.

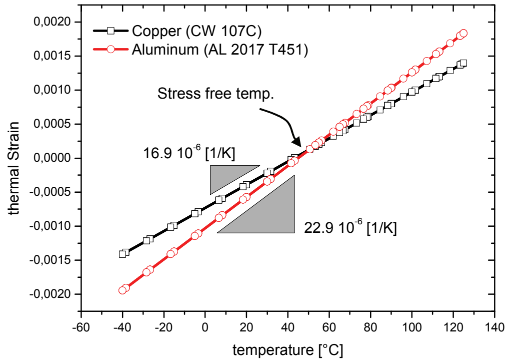

Fig. 7 FEM – results of Aluminum and copper core thermal strain

5 EXPERIMENTAL RESULTS

First experimental results could be determined for the SnAg3.5Cu0.75 solder alloy. The flip-chip specimen was equipped by 4 equal solder joints. This solder alloy is known to be very creep resistant in relation to SnAg3.5 or SnPb37 [8]. Also the stress sensitivity of the solder is very high. That means the dynamic of plastic deformation is strongly dependent on stress (applied force).

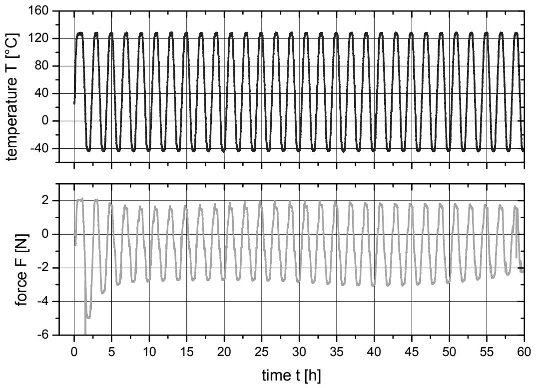

Fig. 8 experimental results, measured temperature and force over thermal cycle time

Fig. 8 shows the measured temperature profile over thermal cycle time. The maximum temperature of +125°C and the minimum temperature -40°C were exactly reached.

In relation to this the applied force at solder joints was observed in situ as described before. It could be determined a force drop during the first 3 cycles. After that, the force level kept constant at approx. 60% of initial force over further 30 cycles, before the forces dropped down. It is assumed the force level keeps at a steady state, in which micro structural changes occur. The experiment ends with the mechanical failure of the solder joints.

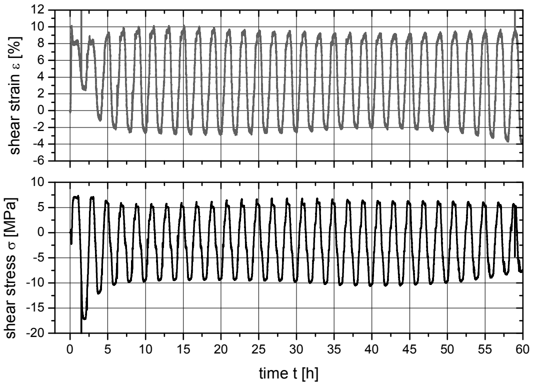

Fig. 9 experimental results, derived shear stress and strain inside the solder joint

A first simple conversation of shear force to stress and deformation to strain were done (see Fig. 9). The stress proceeds proportional to the force. The strain instead increases over the first few cycles form $\Delta\varepsilon = 6\%$ up to 12%. This huge amplitude is the reason for quick weakening of the solder joint strength until 30 cycles. Further experiments will be planned with much lower strain amplitudes. This easily can be done be reducing the aluminum and copper column length (l_0).

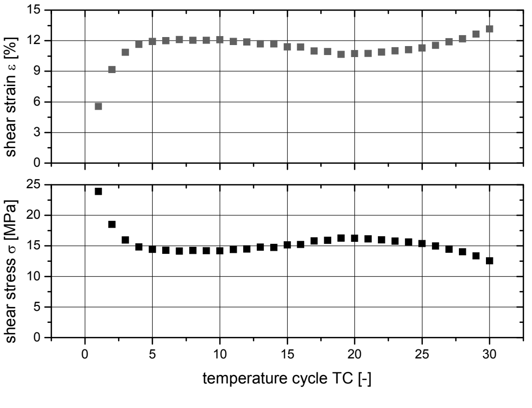

Fig. 10 plotted stress and strain amplitudes of solder joints over thermal cycle time

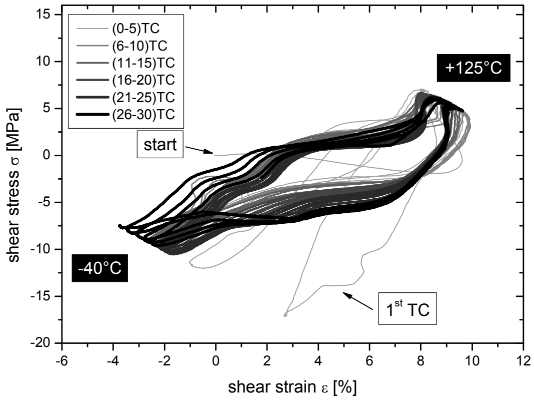

Fig. 11 shear stress vs. shear strain plot of solder joint deformation

In Fig. 11 the derived shear stress and shear strain inside the solder joints is plotted. During the thermal cycles the amplitudes of both parameters change. The strain continuously increases, whereas the stress decreases. At the extreme temperatures the stress-strain relation forms a linear dependency. This may be an indicator of evaluation the fatigue resistance of solder. Using this indicator different solder alloys can be compared to each other and high performance alloys will be selected.

A further indicator could be the dissipated energy release evolution over thermal cycles. The area inside the stress-strain hysteresis represents the plastic work which is needed to deform the solder joints.

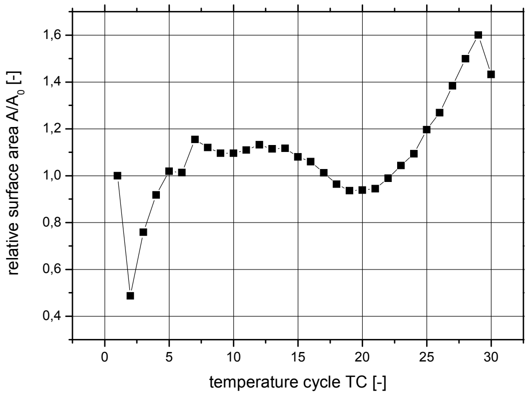

Fig. 12 normalized area inside the stress-strain hysteresis as evaluation of dissipated energy release

6 CONCLUSIONS AND OUTLOOK

The authors have developed a loading frame for in situ force measurement at solder joints during thermal cycle tests. The loading frame was successfully tested and first results could be presented on SnAg3.5Cu0.75 alloy. Further the experiment is supported by FEM-calculations. The FEM-model of the loading frame was successfully calibrated and is prepared for material data extraction from experimental results. Following main technical advances were achieved:

- Realization of thermal driven loading frame for solder fatigue experiment
- In situ force measurement of solder degradation
- High linear behavior of loading frame for easier separation of the plastic and elastic deformation
- Calibrated FEM-model
- Practical proof of functionality on SnAg3.5Cu0.75 solder joints

Following future work is in progress or planned:

- Fatigue comparison of different solder alloys
- Verification of solder creep models by comparing plastic strain per cycle determined by experiment and FEM
- Determination of exact strain amplitudes and dissipated energy by FEM
- Determination of fatigue evaluation behavior of lead-free solders
- Additional observation of electrical impedance of solder joint

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