Combined loading and failure analysis of lead-free solder joints due to creep and fatigue phenomena

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Abstract
Purpose – The aim of this work is the use of specially designed, authoring device to evaluate the strength of solder alloys commonly used in all kinds of electronic and electrical devices that are used in various fields of economic and industrial development to shorten the testing period. By obtaining answers to pervade science questions on how to properly investigate the reliability of solder joints can increase lifespan (uptime) of all electronic devices, and especially those that are used in the process submitted severe external conditions (dust, humidity air, heat, mechanical stress).

Design/methodology/approach – The basic demand for performing the experimental tests is to measure small displacements (order of fractions of micrometers or of single microns) occurring within the sample. The analysis of the displacement values in various environmental conditions (temperature, humidity, current flow) allows estimating how a given material behaves also in a longer time, under normal operating conditions. Unlike a commonly used method, based on measuring the time-to-failure, at which the item is damaged due to accelerated aging, a behaviour of the sample is being tested for the selected duration time and the given loading conditions.

Findings – The theoretical analysis and performed numerical simulations of ATC tests based on developed failure and reliability investigation system (FRIS) imply proposed here combined loading approach a promising and affective method for accelerated reliability tests. Both indentation and FRIS techniques by numerous possibilities of loading conditions seem to be appropriate in order to study the creep and fatigue behaviour. That kind of behaviours can be used by different models which characterize separately the mechanical properties under creep or fatigue tests. In case of creep mode, the displacement is expressed as a function of time where different parameters can be used to represent the creep sensibility.

Originality/value – New device can provide both creep and fatigue phenomena simultaneously and perform tests in digital controlled environmental conditions. That approach enables faster method for testing reliability of solder joints.

Keywords Fatigue, Microelectronics packaging, Creep, Failure analysis, Microindentation

Paper type Research paper

1. Introduction

Fundamental properties of solder joints like electrical signal transmission, heat transportation and structural support means that their existence are essential for the functioning of all electronic devices. Such features also entail consequences connected with reliability problems. Hence, the behaviour of solder joints influences the active service lifetimes of electronic devices, i.e. the uptime in which they can work properly without any dysfunction.

However, keeping all these attributes is extremely difficult due to the different thermo-mechanical loadings that lead to degradation processes in each of them. To solve this issue, new information about simultaneously acting creep and fatigue phenomena is needed. The best solution seems to be to undertake testing using different types of alloys and different reliability examination devices.

Microindentation (indentation in the micron or even sub-micron range) was employed here for analyzing the creep and fatigue behaviours of solder joints. The creep, resulting from the application of a constant load over a certain time, is represented by an original law between the indenter displacement and time. The fatigue due to repeated loading-unloading cycles is characterized by the Manson-Coffin law which is adapted for connecting the plastic indentation strain to the number of cycles. As a result, there will be the possibility to create models describing solder joint behaviour under various work conditions.

The second method which can confirm and verify the authenticity of the above tests is a failure and reliability investigation system (FRIS). This device provides various types of loadings that allow the problem of damage accumulation due to creep and fatigue occurring simultaneously to be analyzed. By applying a cyclic force loading, one can observe both the elastic deformation of a sample and the inelastic deformation due to creep. Analysis of the displacement values in various environmental conditions (force, temperature, humidity, vibration, current flow, etc.) allows an estimation of how
a given material behaves over a long period of time and/or under normal operating conditions.

2. Microindentation technique

Microindentation experiments were carried out in the University of Lille Nord, France. Tests were performed with a micro-hardness CSM 2-107 tester equipped with a Vickers diamond indenter. The load range of the instrument was from 0.1 to 20 N. The load resolution was 100 μN and the depth resolution 0.3 nm; these values being provided by the CSM Instruments Group. In this work, microindentation creep tests have been performed at a constant loading rate of 100 N/min with holding loads ranging from 1 to 20 N to investigate the indentation creep behaviour over 1,800 s of dwell-time. The microindentation fatigue tests were performed during 100 cycles at a constant maximum holding load ranging between 1 and 20 N with a null dwell-time to avoid creep phenomenon. The loading and unloading rates were chosen in order to obtain 1, 2.5, 5, 10 and 15 cycles per minute (Chicot et al., 2013). All these conditions were adjusted to the FRIS testing conditions to enable comparison of the results from the two instruments.

3. FRIS technique

The FRIS was designed for testing creep and fatigue phenomena. The designed method was based on an experimental test setup that, under precisely controlled conditions, allowed testing of the behaviour of samples (solder joints) subjected to factors such as tensile/compressive stress (mechanical loading), temperature cycling (thermal loading), current flow (electrical loading) or humidity. The main parts of the FRIS device were two arms with one fixed arm connected to a force transducer and one movable arm connected to a stepper motor. A force transducer was used to measure the applied force and the stepper motor was used for applying a mechanical loading (force) to the specimen. A capacitance sensor was located between the arms to measure small displacements of the specimen (solder joint). An environmental chamber with a Peltier Cell was used to maintain the specimen at a constant temperature. The operating principle of the FRIS device is shown in Figure 1.

Figure 1 The FRIS device

The main requirement while performing tests was to measure small displacements (in the order of nanometers) arising within the specimen. The force applied to the specimen using the stepper motor caused the distance between the capacitor claddings to increase. The distance was calculated on the basis of measured capacitance. The initial capacitance (and also the initial distance) were established when no force was applied to the arm of FRIS (Figure 1(a)), while the final capacitance/distance was measured when the required force was achieved during a test (Figure 1(b)). The difference between the initial and final measurements of the distance provides information on how the specimen was damaged (geometry of specimen was changed) during testing. Analysis of the displacement values in various environmental conditions (temperature, humidity, current flow) enabled an estimation of how a given material would behave over a longer period, under normal operating conditions. Unlike a commonly used method, based on measuring the time-to-failure, at which the item is damaged due to accelerated aging, a behaviour of the sample was being tested for the selected duration time and the given loading conditions.

The load range was limited by force transducer (0-50 N) and the load resolution (30 mN) was restricted by the stepper motor motion. An arm could be moved 330 nm in one step and displacement measured with a resolution of 5 nm.

4. Experimental

Microindentation tests were performed using a massive block of SAC 405 alloy. This shape of specimen allowed direct examination of its properties. Unfortunately, the size of the specimen was too big to use in the FRIS instrument.

To imitate the above mentioned specimen with one that could be used in the FRIS device, new specimens were prepared. One of them is shown in Figure 2(a) and this kind of specimen was properly able to demonstrate behaviour of the pure alloy. All of them were prepared from pure SAC 307 solder paste in the same way (special form) and using the same environmental conditions (e.g. a paste melting temperature of 280°C). To estimate if a specimen was formed properly, i.e. without any gas cavities inside them, X-ray imaging was performed (Figure 2(b)).
Less solder voids generally mean that a specimen will have more strength and the results obtained are more reliable. However, due to flux located in the soldering paste, which evaporates during heating (one of two steps in creating specimens), keeping this state was sometimes difficult. Therefore, numerical methods were needed to estimate how gas cavities had an influence on the reliability of joints.

4.1 Creep
Creep in electronic assembly is defined as the physical phenomenon of a time dependent increasing irreversible deformation of a material when a constant loading is applied during a specified time-period. All materials are subject to this effect but, for purely visco-elastic materials, the deformation during the creep-period is null after complete unloading. Visco-plastic materials behave in a different manner and for which deflections are time-dependent (Chicot et al., 2013). Creep with time is a combination of both elastic and plastic deformations. Therefore, there are two creep mechanisms:

1. slip inside grains – creep as a result of diffusion and movements of atoms (elastic deformation); and
2. slip along grain boundaries – creep as a result of dislocation (plastic deformation).

Taking into account the above-mentioned effects it can be stated that the examined materials were distinguished by “visco-elastoplastic” behaviour that manifests different stages of deformation:

- instantaneous elasticity (the material undergoes deformation when stress is applied);
- delayed elasticity; and
- viscous flow (deformation increases linearly for a given time and then rapidly leads to failure).

During the dwell-time at the maximum load, the indenter usually continues its displacement for which the magnitude depends on the applied load, the holding time and the temperature (Ma et al., 2008). Figure 3(a) shows examples of the indenter displacements as a function of time resulting from the application of 5, 15 and 20 N.

The same tests were performed using the FRIS device. The results are shown in Figure 3(b). One can observe that the curves in the two figures are similar and, what is more, they are compatible with ordinary creep curves. The first stage of the curve presents a rapid increase of deformation with time. In the second stage, the speed of deformation is constant (steady-state region). In this part both the indentation sizes and the arm displacements increased linearly with time. These results indicate that the microindentation and FRIS techniques were appropriate techniques for this type of analysis. The main difference was the speed of deformation increase because of the different types of alloys used.

The results compiled in Table I from Figure 3(a) and (b) confirm that the two instruments satisfied the requirements needed to perform creep tests.

4.2 Fatigue
In an opposite manner to the creep failure mode, fatigue also occurs, and this is a phenomenon responsible for the development of cracks in electronic elements exposed to a varying cyclic force with time. This leads to periodical local and global stresses occurring, deformations and dissipation of inelastic energy. Fatigue failures are a result of cracking. Thorough analysis of the cracks, their initialization and propagation, allows an estimation and forecasting of fatigue failure (Ellyin, 1996). Xu et al. (2007) showed that the damage mechanism of indentation fatigue results in the nucleation, formation and propagation of microcracks around a flat indentation. They confirmed that the nucleation and accumulation of cavities were responsible for the development of cracks, which is the main damage mechanism during fatigue by indentation (Xu et al., 2007).

Figure 4 shows fatigue curves obtained using the microindentation technique (Figure 4(a)) and the FRIS technique (Figure 4(b)). Both plots demonstrate deformation, which is exhibited in a displacement of 15,982 nm by indentation and 117 nm by the FRIS instrument. Fatigue curves obtained via the FRIS device are presented as hysteresis plots which increase in width to determine the size of displacement (deformation). In the case of indentation, displacement was calculated on the basis of curve width starting from the moment when the indenter reached maximum load for the first time. The maximum indenter displacement was decreasing after each cycle and this was consistent with the hardening phenomenon.

As a result of the results obtained from creep and fatigue tests by indentation, one can create rheological models which could be adequate to adequately present both the creep and fatigue behaviours of the SAC 405 alloy. Chicot et al. (2013) proposed the use of two simple models: a stress exponent which could be used to represent the creep behaviour and the Manson-Coffin law to describe fatigue behaviour while also allowing determination of the fatigue ductility coefficient $\varepsilon_{fmax} = 5.5 \text{ per cent}$ and the fatigue ductility exponent $c = -1.11$ for the SAC 405 alloy (Chicot et al., 2013).

5. Conclusions
Both indentation and FRIS techniques, with their numerous possibilities of loading conditions, seem to be appropriate for studying creep and fatigue behaviour. These kinds of behaviour can be used in different models which characterize separately the mechanical properties under creep or...
fatigue testing. In the case of the creep mode, the displacement was expressed as a function of time, where different parameters can be used to represent the creep sensitivity. The basic and most important parameter was time, or stress-exponent, which could describe a first approach connected to the creep failure, i.e. the phenomena of diffusion, sliding at grain boundaries, dislocation climb or movement of dislocations according to its value, which is usually between 1 and 15 (Chicot et al., 2013). In indentation fatigue, the indenter displacement can be expressed as a function of time, number of cycles or load (Chicot et al., 2013).

6. Future plans

In the future, a new method of testing will be performed. It can be done using a Nordson Dage Bondtester 4000 Plus, which enables the reliability assessment of various joints located on PCBs. The main elements of the device are cartridges, with their small and very precise tips. Thanks to the availability of different cartridges and tips, various experiments can be realized, e.g. pull, push and shear tests with various forces applied to the specimens. One of these, the Hot Bump Pull (HBP), can be suitable for making combined creep and fatigue tests.

Tests using HBP (Figure 5) and the appropriate software from Dage consist of two stages:

1. setup of the test parameters; and
2. positioning of the pin over a solder bump.

First, a temperature profile is created, allowing a user to input the temperature and time criteria for the required reflow and test conditions (Nordson Dage Team, 2011). The simple
interface only requires the desired temperature and time to reach that temperature. The heating and cooling rates, as well as the test execution, are then automatically handled by the hardware and the software (Nordson Dage Team, 2011).

Using this feature, the pin from the end of the cartridge can be fused to the ball and then an accurate push/pull force can be applied to the specimen. Moreover, tests can be performed at different constant temperatures, which is very valuable when performing creep and fatigue tests. These attributes allow repeatable experimentation and thus a better probability for obtaining the same results with subsequent measurements.

After making tests, if a joint has failed, Nordson Dage offers software to perform failure analysis and reports can be generated where force, data, failure mode and image can be presented (Nordson Dage Team, 2011).

**References**


**Further reading**


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**Figure 5** Example of (a) HBP tests using a copper probe on a BGA and (b) a close up of solder ball reflow.

![Figure 5](image-url)