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Reliability analysis of solder joints due to creep and fatigue in microelectronic packaging using microindentation technique

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ABSTRACT

Solder joints in microelectronic are used for electrical signals transmission, heat conduction and structural support. One of the key problems referring to solders in microelectronics is reliability due to typical failure modes as creep and fatigue. The above paper focuses on the experimental measurements and corresponding analysis with the microindentation tests of the SAC 405 solder alloy due to creep and fatigue. The creep, resulting from the application of a constant load during a long 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 law of Manson–Coffin which is adapted for connecting the plastic indentation strain to the number of cycles.

1. Introduction

In microelectronic packaging, the solder joints constituted of tin–lead alloy until these last decades have played a major role in the reliability of the components. But due to the restriction of the use of certain hazardous substances such as lead in electrical and electronic equipment (RoHS regulation) [1], new alloys for solder joints have been developed. Among them, the SAC 405 alloy (S–SnAg4Cu0.5) takes place as a lead-free solder to replace the common tin–lead eutectic alloy (63/37) [2]. Nevertheless, the SAC 405 alloy tends to be more brittle due to a high stiffness and excessive solder interfacial reactions. As mentioned by Chin et al. [2], this leads to higher occurrences of solder joints failure during surface mount assembly, handling operations or in service under thermo-mechanical loadings. Conversely, reliability prototyping of electronic packaging is currently long-lasting and costly. Indeed the usual tests based on thermo-mechanical and cycling loadings can last for a number of months and reflect only the most dominating failure mode e.g. creep and/or fatigue. Therefore appropriate understanding and development of analytical methods and experimental tools for multi-failure criteria analysis could be very helpful. Such works have been originally conducted by Jankowski et al. [3] whom developed a new device to analyze coupled creep and fatigue behaviors of solder joints. This is based on the experimental test setup (FRIS – Failure and Reliability Investigation System) that under precisely controlled conditions allows to test behavior of the sample (solder joints) subjected to the factors such as tensile/compressive stress (mechanical loading), temperature cycles (thermal loading), the current flow (electrical loading) or the humidity [3].

On the other hand, the development during these two last decades of the instrumented indentation equipment allows for a large variety of mechanical testing conditions by indentation. In fact, using load–displacement cycles of the indenter together with different loading and unloading rates allows for analysis of the visco-elastoplastic behavior of materials. Moreover, the maximum indentation load can be maintained during a given time period where the indenter continues to penetrate into the material for which the magnitude of penetration depends on the mechanical behavior of the tested material. Such an indenter displacement observed during the dwell-time at a constant load is representative of a creep phenomenon by indentation and the measurement of power-law creep parameters by instrumented indentation methods, which has been extensively discussed by Su et al. [4]. Besides, successive cycles can be performed using the same maximum load with increasing loading mode to assess the plastic characterization beneath the indenter, thus the phase transformation under indentation stress or the failure of coatings as mentioned by Xu et al. [5] when studying the indentation fatigue behavior of polycrystalline copper. Consequently, instrumented indentation seems to be a suitable technique for separately or jointly realizing coupled indentation conditions, i.e. creep and/or fatigue for example. This is one of the main advantages of such mechanical testing thus allowing to analyze the mechanical behavior of tested material under multiple mechanical sollicitations [6,7]. In this work, a methodology based on the use of the microindentation technique is proposed to study separately creep and fatigue phenomena on the SAC 405 alloy. The objective to model coupled sollicitations by indentation is currently under investigation and will be

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presented in the near future. To limit the number of testing conditions and to compare with the Failure and Reliability Investigation System [3], the indentation testing conditions for creep and fatigue analyses have been chosen according to the FRIS testing conditions.

2. Experimental analysis

Microindentation experiments were carried out with a microhardness CSM 2-107 Tester equipped with a Vickers diamond indenter. The load range of the instrument is from 0.1 to 20 N. The load resolution is 100 μN and the depth resolution is 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 behavior over 1800 s of dwell-time. The microindentation fatigue tests have been performed during 100 cycles at constant maximum holding loads ranging between 1 and 20 N with a null dwell-time to avoid creep phenomenon in this test. The loading and unloading rates have been chosen in order to obtain 1, 2.5, 5, 10 and 15 cycles per minute. Fig. 1 shows an example of load–displacement curves for creep analysis (Fig. 1a) and for fatigue analysis (Fig. 1b) resulting from the application of 15 N and 1 cycle per minute. As it is visible in Fig. 1a, the indenter continues to penetrate into the material during the plateau observed at the maximum load. The total length of this plateau reflects the creep sensibility of the material but its analysis deals with the study of the indenter displacement as a function of time. In Fig. 1b, the maximum indenter displacement after each cycle was decreasing, which thus exhibits the hardening phenomenon. For information, it can be noted that the total displacement reached after 100 cycles under the constant applied load of 15 N, close to 85 μm, is quite similar to the total displacement obtained after 1800 s of dwell-time under the same maximum applied load. The total displacement after creep and cyclic loading is quite similar around 20 μm.

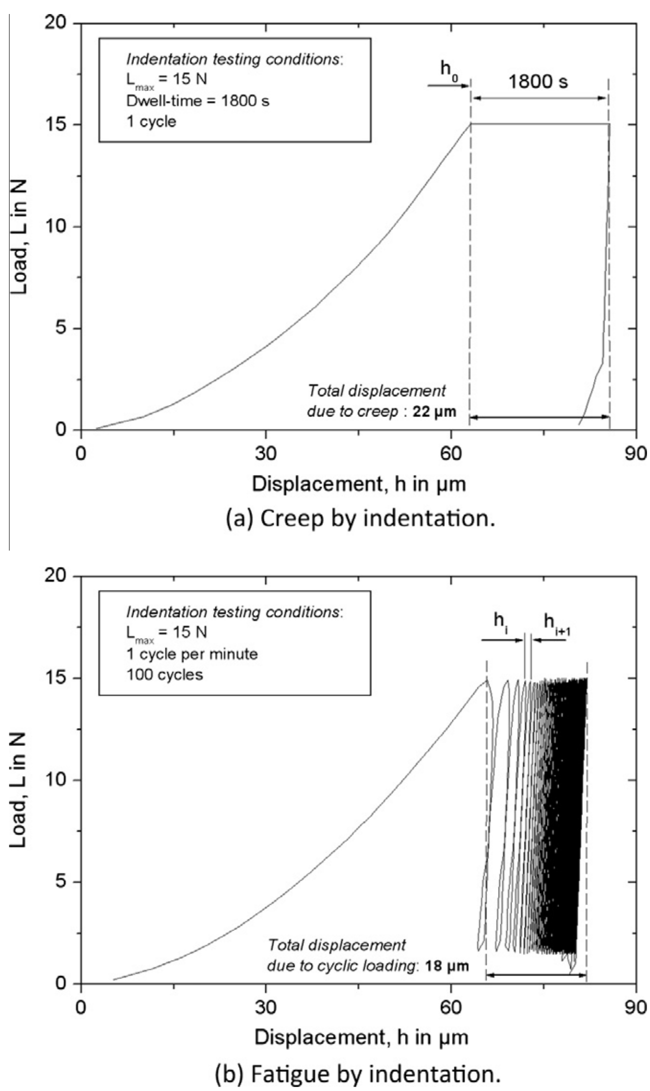

Fig. 1. Example of load–displacement curves obtained under the maximum applied load of 15 N to study (a) the creep phenomenon during 1800 s and (b) the fatigue behavior with 1 cycle per minute.

3. Creep

Creep is a physical phenomenon associated with irreversible deformation of the material resulting from a constant loading applied during a sufficient time-period. For a purely visco-elastic material, the deflection which is observed during the creep-period is null after the complete unloading. Conversely, for a visco-plastic material the residual indentation depth is time-dependent. Usually, creep manifests in time with a part of elastic deformation, which results in the diffusion and movements of atoms, and another part of plastic deformation where dislocations motion is initiated inside the material. In this case when the material exhibits a "visco-elastoplastic" behavior, different stages of deformation can be observed, i.e., the instantaneous elasticity (the material undergoes the deformation when the stress is applied), the delayed elasticity and viscous flow (the stage where deformation increases linearly for a given time and then rapidly leads to material 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 [8]. Fig. 2 shows an example of the indenter displacement as a function of time and resulting from the application of 15 N. The indentation data are taken from the plateau data observed at the maximum applied load of 15 N as given in Fig. 1a.

The indentation creep data shown in this figure present an indentation curve similar to that of an ordinary creep curve. The first stage of the curve records a rapid increase of deformation with time, with a decreasing rate, followed by a steady-state region where indentation sizes increase linearly with time. To analyze the variation of the indenter displacement as a time-function rep-

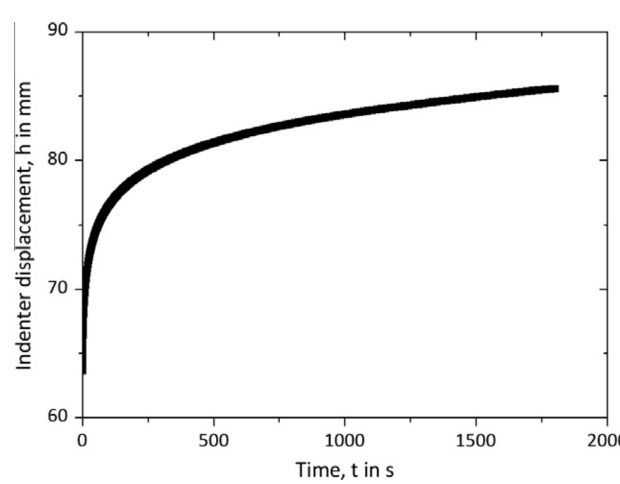

Fig. 2. Indenter displacement versus time resulting from the application of 15 N during 1800 s.