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Microstructural evolutions of Sn-3.0Ag-0.5Cu solder joints during thermal cycling

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ABSTRACT

Temperature-induced solder joint fatigue is a main reliability concern for aerospace and military industries whose electronic equipment used in the field is required to remain functional under harsh loadings. Due to the RoHS directive which eventually will prevent lead from being utilized in electronic systems, there is a need for a better understanding of lead-free thermomechanical behavior when subjected to temperature variations. As solder joints mechanical properties are dependent of their microstructural characteristics, developing accurate solder joint fatigue models means to correctly capture the microstructural changes that undergo the solder alloy during thermal cycling. This study reports the Sn3.0Ag0.5Cu (SAC305) solder joints microstructural evolution during damaging temperature cycles. Electron BackScatter Diffraction (EBSD) analysis was conducted to assess the SAC305 microstructure corresponding to a specific damage level. Investigated microstructural features included the β-Sn grain size and crystallographic orientation, as well as the grain boundary misorientation and Ag_3Sn intermetallic compound (IMC) size. As-reflowed and damaged components were also mechanically characterized using nanoindentation technique. The microstructural analysis of SAC305 solder joints prior to thermal cycling showed a highly textured microstructure characteristic of hexa-cyclic twinning with two β-Sn morphologies consisting of preferentially orientated macrograins known as Kara's beach ball, along with smaller interlaced grains. The main observation is that recrystallization systematically occurred in SAC305 solder joints during thermal cycling, creating a high population of misoriented grain boundaries leading to intergranular crack initiation and propagation in the high strain regions. The recrystallization process is accompanied with a progressive loss of crystallographic texture and twinning structure. Ag_3Sn IMCs coalescence is another strong indicator of SAC305 solder damage since the bigger and more spaced the IMCs are the less dislocation pinning can prevent recrystallization from occurring.

1. Introduction

Electronic equipment for aerospace and military applications can encounter a wide range of environmental stresses mainly due to thermomechanical loadings (temperature variations) [1]. With the RoHS directive preventing the use of lead (Pb), lead-free solder joint fatigue in severe temperature environments has been widely studied amongst the electronic industry and academics [2]. While most studies focus on a macroscopic scale approach when assessing thermomechanical behavior of solder joints, few investigations have been conducted on the effect of thermal cycling on the microstructural evolution of SAC305 solder alloy and the resulting mechanical properties. The microstructure of SAC305 solder interconnects after reflow consists in a network of β-Sn dendrites surrounded by a β-Sn matrix with secondary nanoscale particles of Ag_3Sn (eutectic region). Another IMC phase can appear and depends on the surface finish. For SAC305 solders assembled on pure copper, Cu_6Sn_5 will be formed while $(Cu,Ni)_6Sn_5$ IMCs develop on ENIG finished pads [3]. Large primary IMCs can also be formed before the Sn phase during solidification (plate-like shape for Ag_3Sn and rod-like for Cu_6Sn_5). The β-Sn dendrites orientation is strongly correlated with the crystallographic orientations. As-solidified SAC solder joints generally consist of highly anisotropic β-Sn grains whose size is the same order of magnitude as the joint itself [4,5]. Arfaei et al. studied the influence of solder alloy, volume and pad finishes on the Sn-Ag-Cu solders microstructure and their related thermomechanical properties. Their investigation showed that two principal β-Sn grain morphologies were observed after reflow. These morphologies consist of large macrograins and smaller interlaced grains. They also performed Knoop hardness tests and found out that interlaced grains depicted a higher hardness than the macrograins

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morphology [6]. Lehman et al. suggested that the macrograins morphology forms from a single point nucleation and is the result of the rapid solidification causing recalescence and therefore inhibiting further β-Sn grain nucleation. Their work showed that the macrograin and interlaced morphologies respectively result from {101} and {301} cyclic twins [7].This initial microstructure evolves as thermomechanical damage accumulates in solder joints. Recrystallization is a well-known microstructural change occurring in SAC305 solder interconnects during thermal cycling [8]. As it seems to be the main damaging process involved during thermomechanical fatigue of SAC solder joints, every step leading to the creation of recrystallized grains, and eventually solder crack, need to be thoroughly understood. Research works have been conducted on the effects of the microstructure of as-soldered solder joints on their thermomechanical fatigue behavior. Bieler et al. studied the influence of β-Sn grains orientation on SAC solder joints thermomechanical response. They reported that a worst-case orientation, where the [001] axis of the β-Sn unit cell is parallel to the substrate, generates a maximum CTE-mismatch, therefore leading to earlier failures. Their findings showed that these randomly distributed orientations seem to be responsible for the usual scattering observed with SAC solder joints [9]. The same author further investigated the effect of crystal orientations and temperature cycling on the mechanical response of SAC solder interconnects. In-situ synchrotron X-ray measurements conducted on low-stress Plastic Ball Grid Array (PBGA) components showed that recrystallization process and IMCs coarsening occurring during thermal fatigue tests are unique to each solder joint, making lifetime estimation complex [10]. This work suggests that there is a correlation between the evolution of the initial microstructure (i.e. β-Sn grains orientations and IMCs distribution) after reflow and recrystallization. Several authors have therefore focused their research on the evolution of these microstructural features during thermal cycling. Coyle et al. conducted thermal cycles on PBGA and resistor components to assess the influence of the as-soldered microstructure on the thermomechanical fatigue durability. By controlling the cooling rate, the number of solder reflows, and isothermal aging, they could indeed form different Ag_3Sn IMC particles sizes and spacing. According to this study, conducting temperature cycles with longer dwell times allow to get rid off the initial microstructure dependency [11]. Terashima et al. performed thermal cycles along with Grain Boundary Character Distribution (GBSD) imaging and found a correlation between the higher number of SAC305 Common Site Lattice (CSL) boundaries and its better thermal fatigue lifetime compared to SAC105 solder joints [12]. Yin et al. conducted thermomechanical fatigue tests on SAC305 solder balls and proposed a damage accumulation model based on the evolution of microstructural features. This study showed that recrystallization occurs between 25% and 50% of the characteristic life, the remaining time being controlled by crack propagation in the recrystallized area [13]. The evolving microstructure (Ag3Sn coarsening and formation of recrystallized β-Sn grains) during thermal cycling infers an evolution of solder interconnections mechanical properties. A work conducted by Kanda et al. established a link between the microstructure evolution and the resulting mechanical properties since it focused on the determination of the SAC305 cyclic strain-hardening exponent as a function of the Ag_3Sn particles size and temperature. Their results showed that the exponent was proportional to the reciprocal square root of the average radius of the IMCs, and the effect of temperature on the exponent could be described by the Arrhenius function [14]. Sahaym et al. studied the microstructural coarsening of Ag_3Sn IMCs in SAC305 and SAC105 solder joints during thermal cycling tests. The authors stated that strain-assisted dissolution and reprecipitation of Ag_3Sn particles is accompanied with β-Sn recrystallization when an inelastic strain threshold is reached [15]. Sakai et al. stated that strain hardened metals heated above $T_H = 0.5$ can be subjected to recrystallization [16]. SAC305 alloy begins to become liquid at its solidus temperature equal to 217 °C, meaning that at 20 °C and 125 °C, its homologous temperature is respectively close to $T_H \approx 0.6$ and $T_H \approx 0.8$. In this homologous temperatures range, the time-dependent material response, that is to say viscoplastic behavior of SAC305 solder alloy, is significant and it is therefore likely to observe recrystallization after thermal cycling between −55 °C and 125 °C. The literature survey shows the complexity of the phenomena leading to failure of lead-free electronic assemblies subjected to thermal cycling loading.

This paper aims to provide a better understanding of the SAC305 microstructure evolution during thermomechanical fatigue tests by assessing every step leading to the fatigue crack and correlating the microstructural changes with a thermomechanical damage level. This correlation is performed through the use of a large spectrum of techniques allowing the investigation of the material and mechanical characteristics of SAC305 interconnections. Solder damage is expressed with the creation of recrystallized β-Sn grains through recovery and recrystallization processes. These microstructural modifications come along strain-enhanced Ag_3Sn coarsening which appear to be directly linked to the recrystallization kinetics. Eight industry-representative assemblies consisting in several surface-mount technology components (SMT) including two daisy-chained 900 I/O Wafer Level Packages (WLP900) and two chip resistor (R2512) assembled on a flame retardant (FR-4) multi-layered (8 copper ground planes) printed circuit board (PCB) were designed. Thermal cycling tests were conducted between −55 °C and 125 °C, with a 10 °C·min^{-1} ramp rate and 15 min dwells, until failure of the sixteen WLP900 and R2512 packages to determine the corresponding number of cycles to failure for a 50% failure rate ($N_{50\%}$) using Weibull distribution. Cross-sections were performed on additional test coupons whose electrical continuity was not monitored but were taken out of the thermal chamber at different times throughout thermal cycling duration. An in-depth EBSD analysis was then performed to assess the evolution of selected microstructural features. First, an investigation of the as-soldered specimen was conducted to identify common characteristics and thus to determine the “finger-print” of non-damaged solder joints. Damaged solder interconnects were then considered to study the evolution of these main initial microstructural features and their consequences on the occurrence of recrystallization. A comparison based on nano-indentation hardness measurements was made between an as-reflowed solder joint and a damaged one. Every failed components exhibited solder intergranular cracks in the high strain regions where recrystallization took place along with Ag_3Sn coarsening.

2. Thermomechanical fatigue tests and approach

2.1. Test vehicles and setup

Eight test vehicles consisting of several usual SMT components assembled with SAC305 solder alloy are considered to reflect real assemblies used in the field. Amongst the mounted packages, two specific components are considered for this paper: a Ball Grid Array-like WLP900 distributed by Topline® and a chip R2512 component manufactured by KOA® Speer Electronics. The conformal coating opening diameter for the WLP900 component is 0.4 mm and the pitch between each solder ball is 0.25 mm. Concerning the R2512 resistor, the pad length and width are respectively equal to 3.2 and 0.4 mm. According to their solder joints geometry, their size and their material properties, temperature-induced stress in each package solder joints is very different and they therefore cover a large spectrum of number of cycles to failure. It is worth noting that the WLP is a technology where the package is the same size as the die. Two of each component are assembled per board for a total of sixteen, allowing the statistical analysis of SAC305 solder joints durability. Eight detachable test coupons including each of the selected packages are also designed for the microstructure investigation. The substrate is a 220 × 220 mm, 1.6 mm thick multi-layered (ground copper planes) FR-4 printed circuit board. The board has Electroless Nickel Immersion Gold (ENIG) surface finish on