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Effects of latent damage of recrystallization on lead free solder joints

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ABSTRACT

Recrystallization behavior and microstructure evolution during liquid–liquid thermal shock of lead free solder alloys have been investigated in this study. SAC305 (Sn–3.0Ag–0.5Cu) solder alloy was used as the base solder alloy in which 5 different pitch sizes of ball grid array (BGA) were cycled in liquid–liquid thermal shock with (0/100 °C) profile and almost zero dwell time. The results show that recrystallization takes place in all BGA assemblies regardless of pitch size, but at different times. However, the larger the pitch sizes the sooner recrystallization will take place. This partially due to strain magnitude difference between central and outer joints. Thus larger pitch size coupons were subjected to higher strain magnitude, especially corner joints and hence recrystallization takes place on these coupons earlier. Moreover, it was found that cracks usually start and extend along the recrystallized regions.

1. Introduction

Environmental legislation and market requirements have oriented electronics industry towards lead-free soldering. Today, SnAgCu (SAC) soldering alloys are becoming one of the most favored lead-free soldering alloys. SAC alloys have been studied extensively in terms of material properties, mechanical behavior, solder/substrate interactions, thermomechanical fatigue life analysis, etc. Thermomechanical properties of this material is mainly defined by the stress state in the solder joint, coefficient of thermal expansion (CTE) mismatches between the component and PCB materials, the shape of the solder joints, as well as microstructural characteristics of the solder joints [1–9]. Nowadays, most studies deal with reliability and mechanical properties of this type of solder alloys [1–6]. However the high reliability sectors of industry, which face additional and much more critical challenges, are at very different stages of a transition. The medical electronics industry has started the implementation of lead free solder for increasingly demanding products, while the military/aerospace industry is only dealing with a limited set of issues yet in this regard. Leaders across the latter industry are, however, starting to view lead free soldering as a critical safety and security concern based on the fact that lead free solder materials have better reliability and extended service life compared to SnPb. One action undertaken to address this has been the establishment of the so-called Manhattan Project which led first to the formulation of a 'Current Best Practices' document identifying, among other, the most critical challenges for the assessment of long term reliability [1].

A concern ranked as extremely critical by the Manhattan Project is the effect of combined loading. Most electronics products are in fact subjected to combinations of loads in service. On-board aerospace electronics are, for example, subject to mild but relatively long periods of vibration during flight alternating with shorter periods of harsher vibration during take-off and landing. Assessments of life in service are invariably based, explicitly or implicitly, on the assumption of Miner's rule of linear damage accumulation [6], but recent work has shown obvious break downs of this for lead free solder joints [7]. In one experiment vibration at one frequency and amplitude did for example lead to an extension of the life in subsequent vibration with different amplitude by a factor of two. Perhaps more disturbingly, in another experiment isothermal cycling with one amplitude reduced the life in subsequent cycling with different amplitude by a factor of 3 more than predicted [7]. The potential consequences of this kind of behavior for any kind of cyclic loading are obviously significant.

The most common testing of combined loading is the simultaneous application of temperature cycling and vibration. Even SnPb solder joints have been seen to violate Miner's rule in this more complex scenario [8,9]. As we shall see, this is further complicated by the variation in recrystallization with loading conditions.

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2. Recrystallization

The nucleation of Sn crystals from the melt is notoriously difficult, even heterogeneous nucleation, so high-Sn solder joints tend to under-cool quite substantially during cool-down from reflow. In a typical area array component joint configuration, once a Sn grain finally does nucleate it is usually the only one to do so and a joint is formed by cyclic twinning. In our experience realistic BGA joints usually consist of either a single Sn grain, or of three grains forming a so-called Kara's beach ball structure (see Fig. 1). This makes it particularly easy to detect and confirm later recrystallization [10].

Recrystallization is a process leading to the formation of new equiaxed, presumably strain-free, grains in heavily deformed metals. Recrystallization is characterized by a rapid change in grain structure leading to changes in mechanical properties like tensile and shear strengths. Recrystallization temperature of a given metal is defined as the temperature at which a particular metal with a particular amount of cold deformation will recrystallize completely within 1 h or less. Typically, this falls between 0.4 and 0.7 of the absolute melting temperature. In the case of tin the recrystallization temperature is approximately 30 °C or below [11,12], i.e. recrystallization should tend to occur spontaneously around room temperature if the preceding deformation is severe enough. So, recrystallization tends to play an important role on reliability of lead-free solder joints.

Nucleation of very fine grains is the first step in recrystallization process. In fact, nucleation highly depends on dislocation density making these grains more susceptible to cyclic softening due to grain boundary cracking [13]. Nevertheless, systematic isothermal cyclic loading testing of SAC387 (Sn–3.8%Ag–0.7%Cu) solder samples at temperatures ranging from 25 °C to 125 °C did not lead to significant recrystallization before failure [14].

Not surprisingly, the combination of a sufficient level of deformation, or build up of entangled dislocation networks, with sufficient times and temperatures of annealing did lead to recrystallization. Sundelin et al. reported the possible onset of recrystallization of SAC after creep testing at 105 °C for 200 h [15]. Cold deformation by up to 20% followed by a 48 h anneal at 150 °C led to recrystallization of Sn–0.7Cu samples, while Sn–3.5Ag and SAC357 required even more deformation than that [13]. None of these parameters do, however, seem relevant to wearout in isothermal cycling.

Thermal expansion mismatch induced strains do, however, routinely lead to recrystallization. Terashima et al. [17] showed thermal cycling of Sn–1.2%Ag–0.5%Cu–0.05%Ni solder to lead to recrystallization in the region of strain concentration while the equivalent isothermal annealing at the maximum temperature did not. In fact, thermal cycling routinely leads to such recrystallization [17–20]. This has significant consequences for solder joint reliability, enabling the much easier growth of intergranular cracks along the grain boundaries than the transgranular cracking dominating failure in isothermal cycling. For one thing, the different damage mechanisms should make us question any apparent correlations between isothermal and thermal cycling results, trends, etc.

Xing et al. pointed to another potential concern [4]. The dwell time may affect the number of cycles to failure of lead free solder joints in thermal cycling greatly [3,21–25], a dependence that needs to be accounted for when extrapolating accelerated test results to life in service. More critical, however, is the suggestion that SAC205 solder joints tended to fail by transgranular cracking without recrystallization for sufficiently long dwell times and/or low stresses, i.e. under conditions common under many service conditions [4]. The conditions required accelerating testing and failure, short dwells and/or higher stresses, on the other hand led to a different failure mechanism, recrystallization followed by intergranular cracking, as already discussed above. This trend, which still needs to be reproduced and better quantified, might effectively invalidate common accelerated tests even for relative comparisons, i.e. for design, materials, and process optimization. Characterization of surface damage and residual mechanical strength of the solder joints that experienced longer dwell times at high-temperature extreme exhibited less surface-damage accumulation and less decrease in simple shear strength as compared to those that experienced longer dwell times at low-temperature extreme [25].

Hence, the aim of present work is investigate microstructure evolution and recrystallization behavior of lead-free solder alloys under thermal shock with very rapid cooling–heating profile. Also, this study deals with effect of location of solder joints the reliability of the whole BGA component.

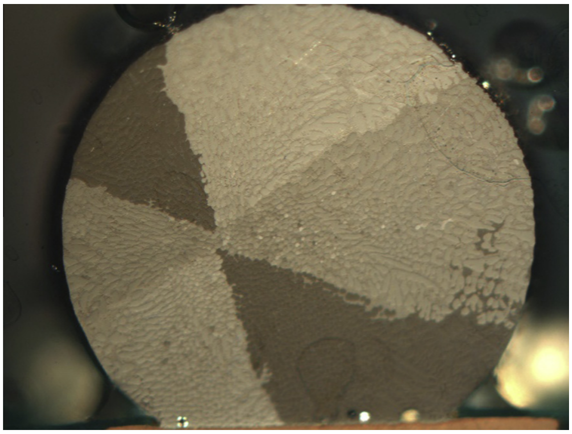

Fig. 1. Kara's beach ball structure in Sn–3.0Ag–0.5Cu alloys (SAC305).

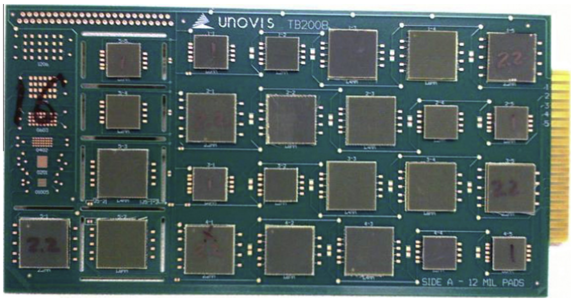

Fig. 2. Test vehicles.

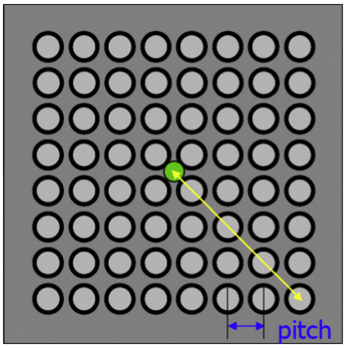

Fig. 3. Schematic picture showing pitch size and distance to neutral point (DNP) [26].