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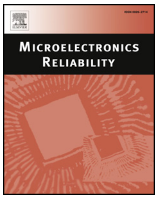

Review paper

The effects of precipitation strengthening and solid solution strengthening on strain rate sensitivity of lead-free solders: Review

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ABSTRACT

Electronic devices are increasingly portable, and often susceptible to damage during handling, transportation, and service. Because of the great variety of stresses to which solder joints are subjected, the mechanical properties of the solder need to be evaluated under a wide range of conditions. The strain rate sensitivity is an essential parameter in understanding the mechanical behaviour of lead-free soldered joints in microelectronics. This literature review is focused on the strain rate sensitivities of lead-free solders and how they are influenced by strengthening mechanisms, including precipitation and solid solution strengthening. Most of the tensile tests and microstructure analysis reviewed showed the dependence of strength on strain rate. However, a clear relationship between solid solution hardening or precipitation hardening and strain rate sensitivity was not revealed in the existing literature.

1. Introduction

The growing dependence of society on functions delivered by electronics means that the reliability of the solder joints that provide the electrically and thermally conductive connections between the circuit elements is of increasing importance. Electronic circuitry is usually designed in such a way that the joints are not exposed to the levels of stress or strain that would result in the sort of failure that occurs in conventional mechanical testing. That means that basic properties such as the 0.1% proof stress, ultimate tensile strength and elongation to failure are not necessarily a useful indication of performance of solder joints in service.

For most electronics failure of solder joints is the result of thermal fatigue. Electronic equipment is made up of a complex assembly of materials with widely varying coefficients of thermal expansion. When operating substantial heat can be generated and although measures are often taken to disperse that heat local heating inevitably results in stress being imposed on the solder joint. Since at normal operating temperatures, typically considered to be in the range $-40\,^{\circ}\mathrm{C}$ to $155\,^{\circ}\mathrm{C}$, tin-based solder alloys are at a high homologous temperature, creep occurs at almost any stress. When operation ceases the assembly cools and the stress is reversed so that conditions for fatigue failure are created. And because of the high homologous temperature recovery processes such as recrystallization in areas of high damage accumulation can occur.

The current model for solder joint failure [1,2] has the following stages:

- Damage accumulation in areas of the solder joint subject to maximum shear strain.
- Recrystallization of the tin in the areas of accumulation damage.
- Grain boundary sliding and grain rotation in the recrystallized area.
- Crack initiation and propagation in the grain boundaries.

The rate of deterioration, and hence the time to failure, is therefore largely controlled by the amount of strain that occurs in each thermal cycle.

Because tin is difficult to nucleate solder joints, particularly the joints to area array packages such a BGA (Ball Grid Arrays) often contain only one or two grains. Since the body centred tetragonal tin crystal is highly anisotropic its response to stress is very dependent on orientation [3–5] but since control of that orientation is difficult that has so far not provided a practical means for improving the service life of solder joints.

The method of improving the reliability of lead-free solder joints that has been most widely applied so far is particle strengthening by the addition of silver. The silver appears in the microstructure as very small particles of Ag_3Sn in the interdendritic regions and these have been found to be very effective obstacles to dislocation movement. Slowing

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dislocation movement slows the damage accumulation that drives recrystallization, the first stage in the thermal fatigue mechanism, so the life of the solder joint in service is increased. At the moment the most widely used lead-free solders are based around the tin-silver-copper eutectic with typically 0.3–4% silver.

It has recently been recognized that the strengthening effect of the silver addition fades as the Ag_3Sn particles coarsen as a result of Ostwald ripening with the consequent increase in the interparticle spacing [6]. In solder that process of coarsening occurs quite rapidly particularly at the higher operating temperature of circuitry such as used in automotive engine management systems and power management systems for electric vehicles. Other particle strengthening additions such as nickel and cobalt suffer from the same problem of loss of effectiveness as a result of Ostwald ripening.

There has therefore been increasing interest in alternative strengthening mechanisms that are more stable and solid solution strengthening has been identified as the best possibility. Additions such as bismuth create distortions in the tin lattice that have been found to be effective in inhibiting the dislocation movement that drive the solder joint failure mechanism.

However, some inconsistencies have been found in the relative performance of particle strengthened and solid solution strengthened lead-free solders under different thermal stress conditions. The two general types of thermal stress test are thermal cycle and thermal shock. In thermal cycle the transition between the high and low temperatures occurs in a single chamber at a controlled rate. In thermal shock the assembly is physically moved between chambers at the high and low temperature so that the temperate change is sudden with substantial temperature differences across the assembly. The consequence is that it is likely that the strain rate to which the solder is subjected is greater in thermal shock testing than in thermal cycle testing. Concern about that effect of strain rate was one of the factors that prompted this literature review.

The strain rate sensitivity of solder alloys is also relevant to the performance of solder joints in the portable devices such as mobile phones that are vulnerable to drop impact [7,8]. In drop impact the failure is more often at the interface between the solder and the substrate or in the laminate on which the circuit elements are mounted rather than in the solder itself. Whether or not failure occurs in drop impact is, therefore, dependent on the response of the solder at the strain rate imposed by the impact. If the solder responds in a ductile manner the stress is not passed onto the interface or the laminate and electrical continuity is maintained. In this situation the strain rate sensitivity of the solder alloy determines the reliability of the joint drop impact.

The effect of strain rate sensitivity of the solder alloy in these two most common solder joint failure modes is the other factor that prompted this review.

There are other mechanisms that lead to solder joint failure such as growth of brittle intermetallics and the associated phenomenon of Kirkendall voids but they are not considered in this review.

2. Strengthening mechanisms of materials

Strengthening methods have been devised to tailor the mechanical properties of materials to demands of their application. The strengthening of a material is a consequence of dislocation interaction with an obstacle. The details of this strengthening mechanism may differ, depending on the characteristics of the obstacles, but the essence of the process is the same, namely resistance of the obstacle to dislocation motion.

Several strengthening (hardening) mechanisms are recognized [9]:

i. Strain (or work) hardening;
ii. Solid solution strengthening–
  a) interstitial atoms,
  b) substitutional atoms;

iii. Grain boundaries and grain size;
iv. Second phase hardening (precipitates, other particles, and impurity atoms).

2.1. Solid solution hardening

Solid solution hardening is a technique for improving the strength of a pure metal by alloying with elements that go into the crystalline lattice of the base metal, forming either a substitutional or interstitial solid solution [9,10]. The local distortion in the lattice due to the alloying element makes plastic deformation more difficult by impeding dislocation motion. Alloying beyond the solubility limit can result in the formation of a second phase.

2.2. Second phase hardening

The strength and hardness of some metal alloys may be enhanced by impeding dislocation motion via the formation of extremely small uniformly dispersed particles of a second phase within the original matrix [9,10]. The second phase particles include precipitates non-soluble particles, such as various oxides, nitrides, borides and carbides and stable and non-soluble impurities [9,10].

The methods for forming and distributing particles include several well established metallurgical techniques. Precipitation hardening occurs when second phase particles precipitate from a supersaturated solid solution. This method is also known as age hardening because the strength develops with time, or as the alloy ages. Often this precipitation is accelerated by controlled exposure to an elevated temperature below the temperature at which the alloying addition is in stable solid solution. Precipitation hardening is commonly employed to create high-strength Al alloys such as are used in the aerospace industry. Other examples occur in Cu-Be, Cu-Sn, and Mg-Al and some ferrous alloys systems.

Precipitation hardening relies on changes in solid solubility with temperature to produce fine particles of a new phase. Precipitation hardening is accomplished by two stages of heat treatments. The first is a solution heat treatment in which all solute atoms are dissolved to form a single phase solid solution. This procedure is followed by rapid cooling or quenching fast enough that there is no time for the diffusion required to nucleate the second phase so that alloy is left in a state of supersaturation. In the second stage the supersaturated solid solution is heated to a temperature within the two-phase region, at which diffusion rates are sufficient to drive clustering and then precipitation of the second phase. For maximum effectiveness as obstacles to dislocation motion the precipitate should form as finely dispersed particles.

2.3. Precipitation strengthening and solid solution strengthening in lead-free solders

Variation in the solder composition or the thermal history of a solder joint significantly affects its microstructure and lifetime [11–15]. In general, a better understanding of these aspects of the materials science of Pb-free solder joint fabrication will lead to optimisation of solder joint performance.

Most of the studies on lead-free solders and soldering have focused on Sn-based alloys. In particular, Sn-Ag alloys, which were the electronics industry's first choice as a replacement for the Sn-Pb eutectic solders which, prior to the implementation of the EU Directive on the Restriction of Hazardous Substances (RoHS) were the standard alloys.

The distribution and morphology of the Ag_3Sn phase in Sn-Ag and Sn-Ag-Cu (SAC) alloys affects their mechanical properties. Kumar et al. reported that Ag_3Sn enhanced the creep resistance, lifetime in accelerated thermal cycling, and strength of Pb-free, SAC solder [16].

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