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A MECHANISTICALLY JUSTIFIED MODEL FOR LIFE OF SnAgCu SOLDER JOINTS IN THERMAL CYCLING

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ABSTRACT

We have shown the life of a SnAgCu solder joint in a typical BGA or CSP assembly in thermal cycling to scale with the time to completion of a network of high angle grain boundaries across the high strain region of the joint. This provides for a credible materials science based model. In-depth studies did however show this to require significant temperature variations. Isothermal cycling may also lead to recrystallization, albeit at a much lower level depending on alloy, processes, and cycling parameters, but a quantitative model would need to be completely different. The question therefore arises as to how large a cycling temperature range is required for our model to apply. We present results indicating that repeated cycling between 20^{o}C and 60^{o}C should be sufficient, i.e. the model should allow for extrapolation of accelerated test results to realistic service conditions.

Many practical applications involve a combination of thermal excursions and mechanical cycling, and there is little doubt that thermal cycling induced recrystallization will tend to lead to much faster crack growth through the solder in subsequent vibration, etc. We discuss how this greatly complicates the definition of a conservative but still practical accelerated test protocol.

Key words: Reliability, thermal cycling, recrystallization, fatigue, service conditions, Pb-free solder.

INTRODUCTION

Almost all reliability assessment is, at least implicitly, focused on the anticipated life in service. In the microelectronics industry the most accurate predictions of long-term life are usually based on accelerated testing together with some way of extrapolating the test results to the different combinations of stress, temperature, time, atmosphere, humidity, etc. characterizing service conditions. This of course requires a quantitative model.

The overwhelming majority of reliability tests conducted by the industry are so-called 'engineering tests' in which the focus is usually not on the quantitative prediction of life in service. However, even relative comparisons between alternatives or against generic specifications rely on an assumed correlation between the accelerated test results and performance under realistic service conditions. In the absence of a very large empirical data base for the specific materials and designs in question, which is not yet available for lead free solder joints in long term service, confidence in such a correlation requires a mechanistically justified model.

When it comes to the long-term life of microelectronics assemblies a major concern, aside from defects which are addressed by mitigation rather than life assessment, is wear out of the solder joints. Thermal mismatch induced stresses usually lead to failure of such joints by solder fatigue. Significant knowledge and understanding has by now been gathered with respect to damage in, and failure of, SnAgCu solder joints. A quantitative model is emerging, but for now the most useful result is that the mechanistic insight allows for better confidence in comparisons. Thus, we have used this to argue that Ball Grid Array (BGA), Chip Size Package (CSP), and Thin Small Outline Package (TSOP) assemblies may be compared in conventional accelerated thermal cycling [1], whereas Quad Flat No-Lead (QFN) and surface mount passive assemblies are likely to have different rate controlling mechanisms and thus acceleration factors [1, 2].

A more general concern, and one shared by all reliability engineers, is that the damage mechanism controlling failure in an accelerated test is ***different*** from the one dominating in service. It is in fact not enough that the same damage mechanisms are involved, a safe correlation between test results and performance in service requires the same mechanisms to be rate controlling. We shall illustrate this concern in our discussion of damage due to combinations of thermal excursions and mechanical cycling below.

First, however, the following section briefly outlines our current understanding of thermal cycling induced damage and failure. After that we describe and discuss experiments intended to ascertain that the same mechanisms are likely to be rate controlling in accelerated thermal cycling and in a relatively benign 'office environment' where on-off cycles may only lead to variations from room temperature to an operating temperature of 60^{o}C.

THERMAL CYCLING MODEL

Realistic SnAgCu solder joints are almost always the result of a single solidification event leading to a so-called 'cyclic twinning' structure of the Sn grains. The up to three unique Sn grain orientations differ from each other by roughly 60^o and are separated by low-angle twin boundaries. In relatively large, BGA and CSP scale, solder joints we end up with either a single Sn grain or a so-called 'beach-ball' structure (Fig. 1). Depending on the combination of solder alloy, pad finishes, impurities, and solder volume smaller joints may exhibit an interlaced twinning structure with a lot more twin boundaries (Fig. 2). In neither case, however, do the boundaries appear to facilitate crack growth in cycling.

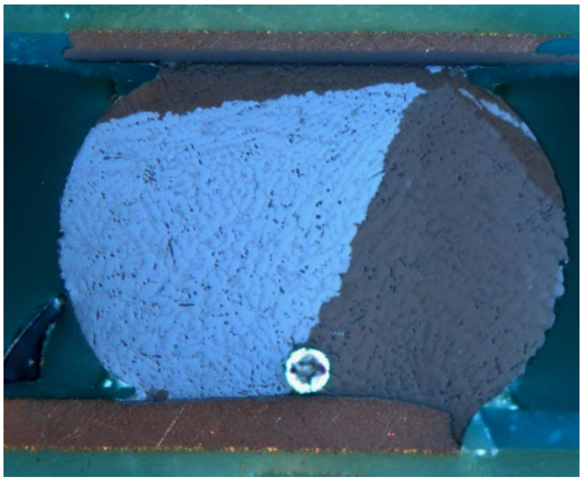

Figure 1: Cross polarizer image of SnAgCu BGA joint cross section showing boundaries ('beach ball') between three large Sn grains [1].

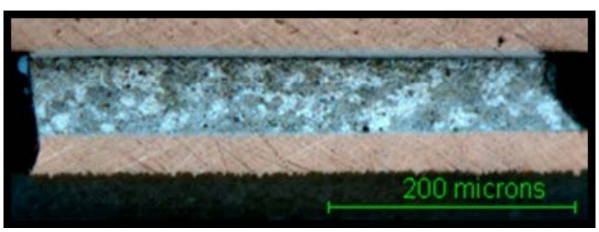

Figure 2: Cross polarizer image of LGA solder joint showing interlacing of the three Sn grain orientations [1].

Using an optimized dye-and-pry approach we showed [3] crack initiation to occur very early in thermal cycling of BGA assemblies, after less than 5% of the characteristic life, $N_{63.2}$. However, transgranular crack growth remained relatively slow for quite a while after that. We believe this to be the reason for reports of a significant crack initiation time. An eventual strong acceleration of the crack growth was found to coincide with the completion of a network of high angle grain boundaries across the high strain region of the joint due to recrystallization of the Sn grains [4], and cracks are indeed commonly seen to have propagated along the new grain boundaries (Fig. 3). The same behavior was observed for TSOP joints (Fig. 4), and dependencies on thermal cycling parameters suggested similar acceleration factors as well [1].

A similar scenario appears to apply to interlaced twinning structures in small solder joints, such as in LGA and flip assemblies, except that here recrystallization seems to be delayed by cycling induced migration of the twin boundaries first driving the structure towards more of a 'beach ball' configuration [2, 5]. Not surprisingly, acceleration factors therefore appear to be slightly different [5].

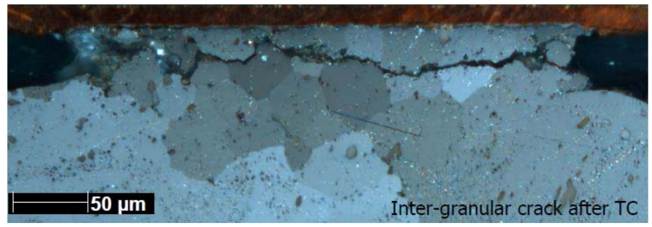

Figure 3: Cross polarizer image of SnAgCu BGA joint with crack along grain boundaries in recrystallized region after accelerated thermal cycling [1].

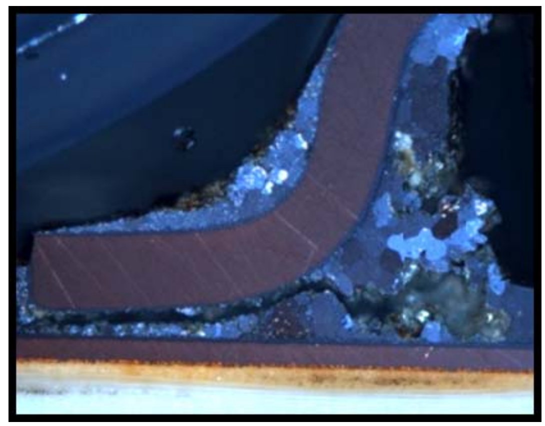

Figure 4: Cross polarizer image of SnAgCu TSOP joint with crack along grain boundaries in recrystallized region after accelerated thermal cycling [1].

While the observation of fatal cracks through a recrystallized region is not anything really new [6-12], the discovery that the completion of the network of grain boundaries in BGA joints would invariably occur within 25-50% of $N_{63.2}$, independently of the cyclic strain range, temperature range, and dwell time, is [4]. This offers intriguing possibilities. Recrystallization appears to be a rate limiting mechanism as far as failure is concerned, so if we can predict the time to completion of recrystallization across the joint, we can predict life. In fact, even if the fraction of life is not always the same under conditions outside of the parameter regime considered by Yin et al. [4], recrystallization may still be rate limiting. For small solder joints indications would be that twin boundary motion together with recrystallization might be rate limiting.

A general, ***quantitative*** model of the recrystallization still offers significant challenges. However, progress towards a practical model continues. Meanwhile, the purpose of the present effort is to ascertain whether recrystallization is still likely to be rate controlling as far as the long-term life under 'office environment' type service conditions is concerned.

EXPERIMENTAL

The present experiments employed specially balanced model test vehicles designed, among other, to minimize warpage in assembly and test. The components were fabricated by sandwiching 0.5mm thick bare Si die between 0.4mm thick FR-4 laminate substrates with a rigid flip chip underfill material (Fig. 5). 20mil (0.5mm) diameter Sn-3.0Ag-0.5Cu wt.% (SAC305) solder balls were reflowed onto electroless nickel immersion gold (ENIG) coated solder mask defined pads on the components. The 256 pads were arranged in 4 perimeter rows with an 0.8mm pitch (Fig. 6). Flux was printed onto the pads before placement and reflow was done in a nitrogen ambient with less than 50 ppm O_2 using a Vitronics - Soltec 10-zone full convection oven and a profile with a 245^{o}C peak temperature and 45 seconds above liquidus.

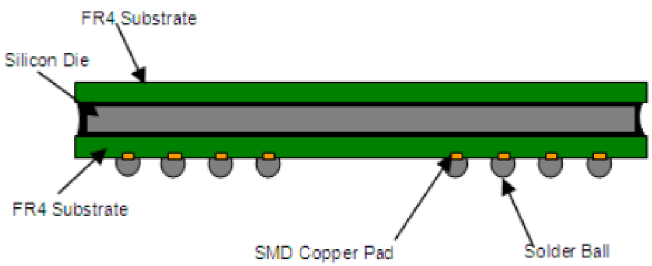

Figure 5: Side view sketch of fully balanced model BGA component

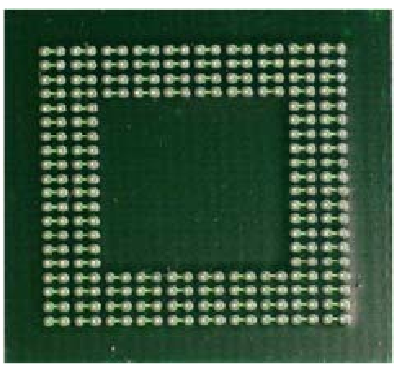

Figure 6: Bottom view of model BGA component

SAC305 solder paste was then printed onto 16mil (0.4mm) diameter OSP coated Cu pads on a 4-layer 62mil (1.55mm) thick printed circuit board, and the components were placed and attached in the same kind of reflow process (above).

Assemblies were subjected to thermal cycling with 10^{o}C/min ramp rates and 10 minute dwells at the maximum and minimum temperatures, and samples were removed after different numbers of cycles for cross sectioning and cross polarizer microscopy. Three different profiles were considered: 0/100^{o}C, -40/60^{o}C, and 25/100^{o}C.

RESULTS AND DISCUSSION

The long-term fatigue life of SnAgCu solder joints in BGA, CSP, TSOP, LGA and flip chip assemblies in thermal cycling appears to be governed by cycling induced recrystallization of the Sn grains, which ends up forming a network of high angle grain boundaries across the high strain region of the joint, followed by rapid crack growth along these boundaries [2, 3, 4, 13, 14]. This failure mechanism competes with transgranular crack growth. Cracks initiate almost immediately, long before any significant recrystallization, but in conventional accelerated thermal cycling they propagate only slowly until the completion of the above mentioned grain boundary network [3]. The question remains, however, whether the same is also true for the much milder thermal cycles characteristic of long-term service conditions.

Effective recrystallization does require significant temperature variations. Isothermal cycling of SAC305 solder joints at any temperature between room temperature and 125^{o}C did not lead to significant recrystallization before failure [15, 16]. Room temperature cycling of SAC205 did cause more recrystallization, but not enough to form a network of grain boundaries before failure by transgranular crack growth [17].

Systematic studies of combinations of pre-aging, room temperature shear cycling and short anneals at elevated temperatures showed that as-reflowed SAC105 joints recrystallized more readily than SAC305, and that recrystallization of the latter is significantly enhanced by aging induced coarsening of the secondary precipitates [14, 18]. It is well established that strain enhanced diffusion in thermal cycling provides for rapid precipitate coarsening [19-22]. Importantly, significant recrystallization required repeated alternations between the pile-up of dislocations at low temperature and the coalescence and rotation of dislocation cell structures at high temperatures.

This explains why completion of a recrystallized region across the joint can be viewed as a rate controlling mechanism for failure in thermal cycling, while that is not so for failure in isothermal cycling.

Effect of High Temperature: For a given combination of pre-aging, shear fatigue cycling, and annealing times the most effective recrystallization was achieved with an annealing temperature of 100^{o}C [14]. Annealing at 70^{o}C or 125^{o}C for the same amount of time gave less recrystallization. The question thus arises whether an operating temperature of, for example, 60^{o}C in service would be sufficient to cause effective recrystallization before failure by transgranular crack growth. Not only is the ‘annealing’ temperature itself reduced, but so is the cycling induced precipitate coarsening.

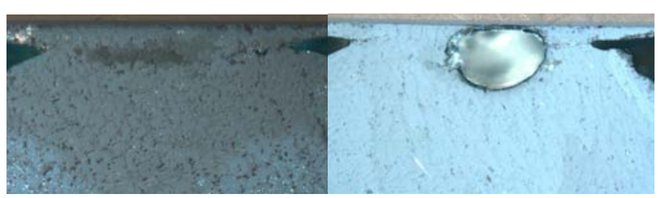

Figure 7: Cross polarizer images of SAC305 corner joints after 400 cycles of 0/100^{o}C (left) or -40/60^{o}C (right).

Figure 7 shows representative cross sections of corner joints in our BGA assemblies after completion of 400 cycles of 0/100°C and -40/60°C. Neither of the joints is close to failing yet, but the 0/100°C cycling has led to significant recrystallization in the high strain region at the top. Empirical experience suggests that lower temperatures should lead to slower failure, for the same ΔT, and indeed the -40/60°C cycling led to little or no recrystallization at this stage.

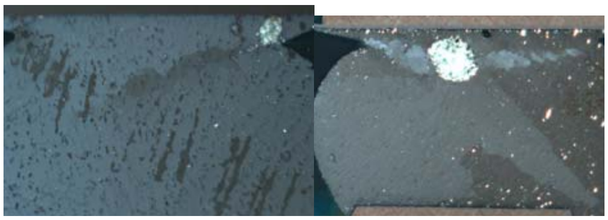

Figure 8: Cross polarizer images of SAC305 corner joints after 900 cycles of 0/100°C (left) or -40/60°C (right).

After 900 cycles there seems to be evidence of extended recrystallization for both temperature ranges (Fig. 8).

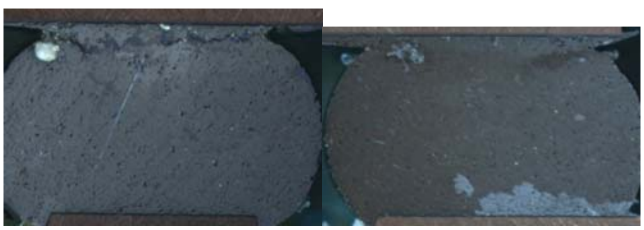

Figure 9: Cross polarizer images of SAC305 corner joints after 1300 cycles of 0/100°C (left) or -40/60°C (right).

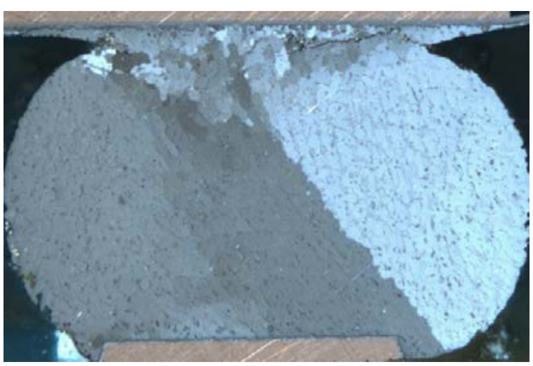

Figure 10: Cross polarizer image of SAC305 corner joint after 1300 cycles of -40/60°C.

After 1300 cycles of 0/100°C recrystallization has led to a continuous network of grain boundaries across the joint, and crack growth along it is almost complete (Fig. 9 left). The joints subjected to 1300 cycles of -40/60°C, on the other hand, still showed only limited recrystallization (Fig. 9 right).

Only after 1730 cycles of -40/60°C is the network of new grain boundaries across the joint complete and significant crack growth is evident (Fig. 10). The joint is still quite far from failing, but it is clear that a 10 minute dwell at 60°C after each excursion to low temperatures is sufficient to cause effective recrystallization and enable rapid crack growth.

Effect of Low Temperature: Of course, annealing at a sufficiently high temperature is not enough to cause extensive recrystallization. Such annealing has to continuously alternate with excursions to a sufficiently low temperature to ensure the effective pile up of dislocations. The question thus arises whether turning off our computer and let it cool to room temperature is sufficient for this.

Figure 11 shows representative cross sections of SAC305 solder joints after exposure to 971 cycles of 25/100°C. In this case recrystallization has led to a continuous network of grain boundaries across the high strain region of each joint, while crack growth is still quite limited. It thus appears that room temperature is sufficiently low to ensure effective pile up of dislocations.

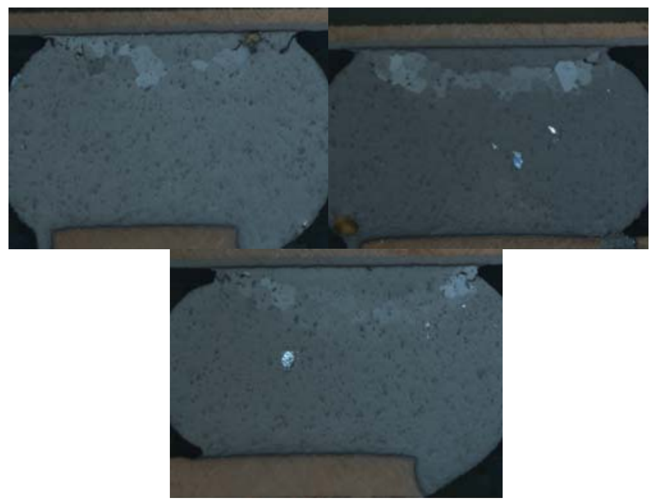

Figure 11: Cross polarizer images of SAC305 joints after 971 cycles of 25/100°C.

Combinations of Thermal Excursion and Mechanical Cycling: As long as vibration, bending, shock, etc. remain completely negligible, such as might be expected for servers and desk top computers, it thus appears that our emerging thermal cycling model may apply under even rather mild service conditions. Of course, different combinations of strain ranges, dwell times, heating/cooling ramps, alloys and pad finishes may affect this.

A more general concern is that many practical applications involve a combination of thermal excursions and mechanical cycling [13, 23]. As documented in detail in a forthcoming publication life in isothermal cycling is determined by transgranular crack growth and ends after the accumulation of a given amount of inelastic energy (work).

There is an obvious need for a practical approach to the assessment of reliability under a realistic combination of repeated mechanical loading and thermal excursions. Experimental assessments may, however, be dangerously misleading unless it can somehow be ensured that the consecutive or concurrent combination closely mirrors the combination of concern in service [13, 23].

A first requirement is that the failure mode is the same [23]. An initial shock loading may for example not lead to damage visible in any cross section but still cause solder joints to fail prematurely by pad cratering in subsequent thermal cycling [24]. On the other hand thermal cycling induced recrystallization may significantly weaken ***and*** soften the solder itself, so that the failure mode in subsequent bending or vibration changes from cratering or intermetallic bond failure to solder fatigue.

Even a combination of, say, thermal cycling with a level of vibration that would have been sufficiently mild to ensure solder failure by itself may easily lead to a change in failure mode. Recrystallization is almost certain to allow for much faster crack growth, and no longer transgranularly, in subsequent vibration.

Finally, even before recrystallization thermal cycling already leads to significant coarsening of the secondary precipitates, and thus to strong changes in the solder properties. The primary effect is here the softening of the solder, leading to much greater inelastic energy deposition (work) per cycle in vibration. Unlike in thermal aging strain enhanced precipitate coarsening is concentrated in the high strain region of the joint, leading to much greater increases in the inelastic energy deposition there.

Overall, while we have established the generic understanding to rationalize test results and discuss potential effects of combined mechanical and thermal loading [13], much more systematic studies are required before we can propose relevant accelerated test protocols. For a start, we suggest that systematic studies of the effects of temperature and strain ranges (S-N curves for different temperatures) after thermal cycling induced recrystallization may help define a meaningful conservative test. However, such a test would only apply to solder failures and not account for competing failures through the intermetallic bond or by pad cratering. Also, it would not account for potential order of magnitude effects of amplitude variations on solder fatigue life [25-29].

CONCLUSIONS

The rate of failure of SAC305 solder joints in BGA, CSP, TSOP, flip chip, or LGA assemblies in thermal cycling is controlled by the recrystallization induced formation of a network of grain boundaries across the high strain region. This mechanism does require numerous repeated alternations between pile up of dislocations at low temperature and the coalescence and rotation of dislocation cell structures at high temperature. However, a maximum dwell temperature as low as $60^{o}C$ and a minimum dwell temperature as high as $25^{o}C$ appear to be sufficient for this to be the dominant mechanism, i.e. conventional accelerated thermal cycling should be relevant for thermal mismatch induced failure under even relatively benign service conditions.

Many realistic service conditions involve a combination of thermal excursions and repeated mechanical loading, e.g. vibration. Depending on the details this may lead to failure much faster than predicted based on Miner's rule of linear damage accumulation. Research to establish an accelerated test approach aimed at conservative assessments for those cases where solder fatigue is the dominant failure mode is proposed.

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