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Solder joint reliability under realistic service conditions

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ABSTRACT

The ultimate life of a microelectronics component is often limited by failure of a solder joint due to crack growth through the laminate under a contact pad (cratering), through the intermetallic bond to the pad, or through the solder itself. Whatever the failure mode proper assessments or even relative comparisons of life in service are not possible based on accelerated testing with fixed amplitudes, or random vibration testing, alone. Effects of thermal cycling enhanced precipitate coarsening on the deformation properties can be accounted for by microstructurally adaptive constitutive relations, but separate effects on the rate of recrystallization lead to a break-down in common damage accumulation laws such as Miner's rule. Isothermal cycling of individual solder joints revealed additional effects of amplitude variations on the deformation properties that cannot currently be accounted for directly. We propose a practical modification to Miner's rule for solder failure to circumvent this problem. Testing of individual solder pads, eliminating effects of the solder properties, still showed variations in cycling amplitude to systematically reduce subsequent acceleration factors for solder pad cratering. General trends, anticipated consequences and remaining research needs are discussed.

1. Introduction

The overwhelming majority of reliability tests are so-called 'engineering tests' focused on comparisons between alternatives or to an established requirement. All of these are of course intended to reveal something about failure in service. This poses more challenges than commonly realized. Notably, realistic long-term service conditions are almost never well represented by cycling with fixed amplitudes. Variations in amplitude tend to lead to permanent changes in the solder properties, affecting not only the solder fatigue but also damage accumulation in the intermetallic bonds and the underlying laminates.

The present work offers a brief review and update of our knowledge and understanding of these issues. Variations in cycling amplitude are most commonly accounted for by the assumption of Miner's rule of linear damage accumulation. According to this [1], a solder joint should fail when the Cumulative Damage Index

$$CDI = \sum \frac{n_i}{N_i} \quad (1)$$

equals 1. Here n_i denotes the number of cycles with a particular amplitude 'i' and N_i is the number of cycles to failure at this amplitude. However, we have shown this and other damage accumulation rules to break down in isothermal cycling of Sn3Ag0.5Cu solder joints [2–4]. After one or more changes in amplitude the remaining life was sometimes 5–10× lower than predicted by Miner's rule. This was explained in terms of a partially permanent softening of the solder leading to greater inelastic energy deposition and thus damage per cycle [2,4].

In the following we shall show the same trends for the low-Ag alloys more commonly used in applications where the primary concerns are isothermal cycling and shock. This kind of loading may of course often lead to failure of an intermetallic bond layer or by pad cratering. The propagation of damage through the laminate under the contact pads is not only sensitive to variations in the solder properties, it also would not obey Miner's rule even if this was not the case [5]. We shall show the violation of Miner's rule to get stronger as the amplitude is reduced. As far as solder failure is concerned we shall also show Miner's rule to break down in thermal cycling, but we shall argue that the reason is different here. Based on our understanding of the different mechanisms we shall finally predict the generic consequences of different combinations of thermal excursions and shock or vibration.

2. Experimental

0.2 mm pitch wafer level Chip Scale Package (CSP) assemblies with Sn3.5Ag1.0Cu wt% joints on a two layer 1.55 mm thick printed circuit board were subjected to thermal cycling with 10 °C/min heating and cooling rates and 10 min dwells at both extremes. Sets of 21–45 assemblies were either cycled to failure in 0–100C, 0–75C or 25–75C, or they were first subjected to a certain number of cycles with one temperature range and then cycled to

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failure with another one. Failures were determined by event detection. The high strain assemblies were selected because they allowed us to access cycling ranges relatively close to realistic service conditions in relatively short tests.

The properties of realistic SnAgCu solder joints are known to vary strongly within an assembly, primarily due to the extreme anisotropy of the Sn grains. Cycling of individual joints in an Instron micromechanical tester allowed for the in situ monitoring of load vs. displacement and thus the measurement of an 'effective joint stiffness' and work per cycle [2]. This has led to mechanistic insights into the effects of amplitude variations on individual joints [2,4]. For this purpose 0.75 mm diameter Sn1.2Ag0.5Cu0.05Ni and Sn1.0Ag0.5Cu wt% solder balls were fluxed and soldered to 0.55 mm diameter Cu pads in a conventional full convection mass reflow oven and then tested at room temperature.

So-called 'Hot Bump Pull' testing of metal defined contact pads on a printed circuit board allowed for the quantification of the load on each individual pad, eliminating any effects of solder properties or board stiffness [6]. For this purpose Sn4Ag0.5Cu balls were soldered to 0.55 mm diameter Cu pads and to a 0.5 mm diameter Cu wire. The wire was oriented at 30° to the surface normal to best replicate the combination of torque and tension exerted on the pad by a corner joint in a typical CSP assembly [6]. The wire was loaded in cyclic tension until failure. Microscopy confirmed that failure occurred by crack growth through the underlying laminate ('cratering'). The fatigue life was measured as a function of load amplitude. Some pads were first subjected to a load of 900 gf in order to induce initial damage in the laminate before cycling to failure at lower amplitudes.

3. Results

Solder failure mechanisms are completely different in thermal than in isothermal cycling, as are apparent reasons for variations in solder properties.

3.1. Isothermal cycling

In isothermal cycling we find the effective rigidity of the solder after initial hardening to decrease with increasing amplitude (Fig. 1). More importantly, this trend includes a 'memory' effect when the cycling amplitude is varied.

Fig. 2 shows the effective stiffness of one of the Ni doped joints vs. number of cycles. The joint was first subjected to 50 cycles with 12 MPa amplitude, leading to initial hardening after which the stiffness levelled off. The amplitude was then raised to 24 MPa,

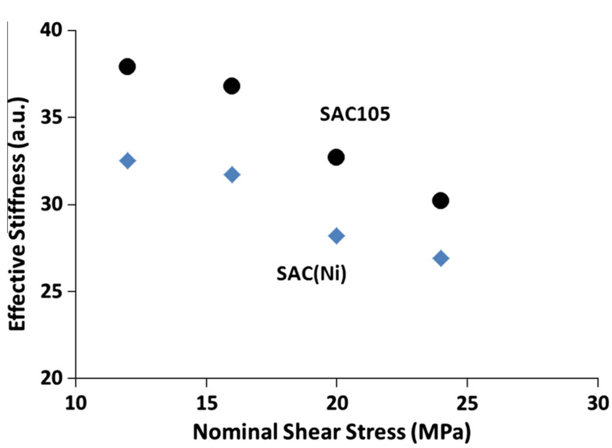

Fig. 1. Average initial load–displacement slope after initial hardening vs. cycling amplitude for Sn1.2Ag0.5Cu0.05Ni and Sn1Ag0.5Cu joints.

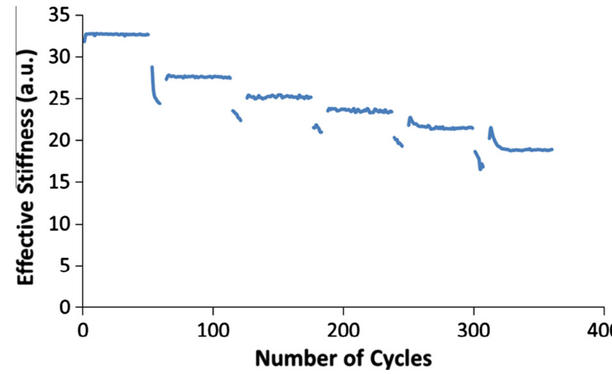

Fig. 2. Load–displacement slope (linear regime) vs. number of cycles for Sn1.2Ag0.5Cu0.05Ni joint in repeated sets of 50 cycles @12 MPa + 7 cycles @24 MPa amplitude.

leading to an immediate reduction in stiffness. This part would seem consistent with the trend in Fig. 1. However, as we returned to the 12 MPa amplitude, after 7 cycles at 24 MPa, the joint did not return to the corresponding higher stiffness. Repeating this sequence led to further permanent reductions in stiffness, the total reduction increasing with the number of times we return for another set of high amplitude cycles. It also increases with the number of cycles in each set, but slower and only up to a few cycles. The strongest effect is therefore observed for a large number of brief excursions to a higher load.

Fig. 3a shows the inelastic energy deposition (work) per cycle corresponding to the stiffness variations in Fig. 2. The initial hardening in cycling to 12 MPa led to a drop in the energy deposition, after which this stabilized until the amplitude was raised. Cycling to 24 MPa of course led to a considerably higher energy deposition there, but after returning to the 12 MPa amplitude the work per cycle remained higher than before. This behavior is seen more clearly in Fig. 3b where the scale was changed so that only the work done with the 12 MPa amplitude is included. Every excursion to the higher amplitude leads to a higher rate of energy deposition.

Separate effects of amplitude variations were observed for failure by pad cratering. Testing of individual solder pads where the load is measured directly, so that the solder properties do not matter, showed the exposure to a high load to reduce the subsequent life in cycling at a lower load amplitude by more than predicted by Miner's rule. What is worse, as shown in Fig. 4 the relative effect of a given high load increases as the low amplitude is reduced.

3.2. Thermal cycling

Our ultra fine pitch wafer level CSP assemblies were first cycled to failure in 0–100C, 0–75C and 25–75C cycling, respectively. Fig. 5

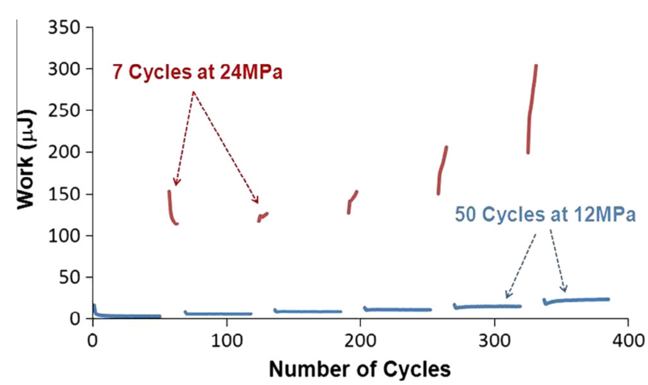

Fig. 3a. Work per cycle vs. number of cycles for Sn1.2Ag0.5Cu0.05Ni joint in repeated sets of 50 cycles @12 MPa + 7 cycles @24 MPa amplitude.

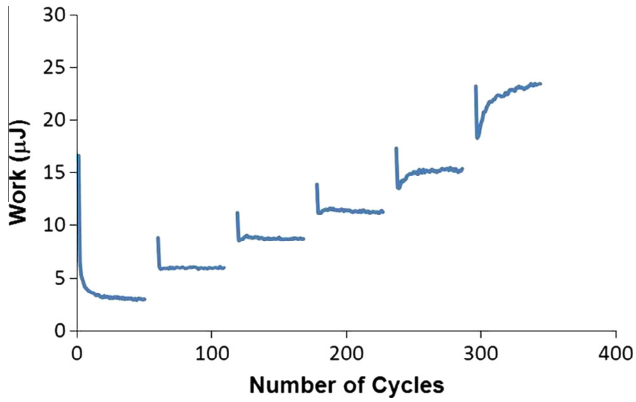

Fig. 3b. Data from (Fig. 3a) on scale better reflecting work per cycle in the different sets of 50 cycles @12 MPa.

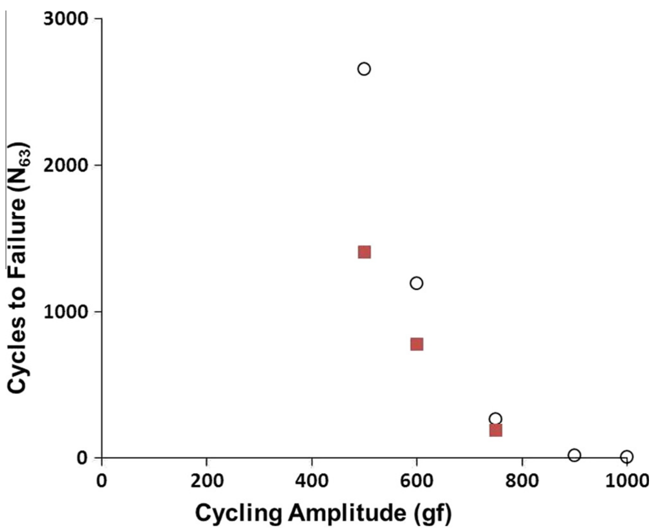

Fig. 4. Average number of cycles to failure by pad cratering vs. cyclic load amplitude. Squares – after exposure to 2 cycles with amplitude of 900 gf.

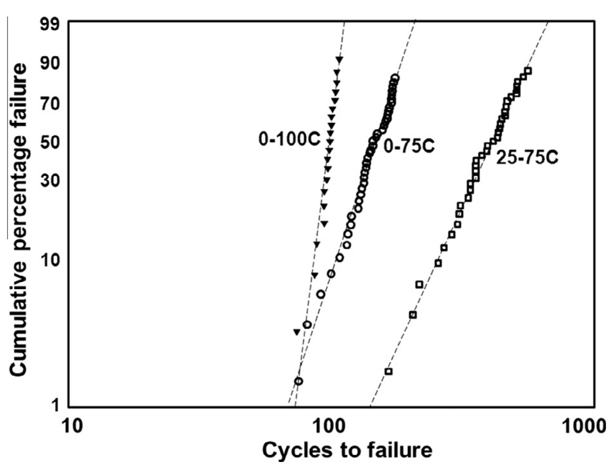

Fig. 5. Cumulative failure distributions for thermal cycling of ultra-fine pitch WL-CSP assemblies with different (fixed) minimum and maximum temperatures.

shows the resulting cumulative failure distributions on a Weibull form. 0–100C cycling is extremely harsh for these assemblies, and both the characteristic life (N_{63} = 101 cycles) and the statistical scatter (shape factor β = 13.9) are low. The scatter in 0–75C and 25–75C cycling is much more typical of area array solder joints in common accelerated thermal cycling tests (β = 5.4 and 4, respectively).

Another set of assemblies was first cycled to 37% of the characteristic life (N_{63}) in 0–100C, which should leave 63% of life in any other cycle according to Miner's rule. However, following this with cycling to failure in 25–75C we found only 187 cycles, or 42% of the corresponding N_{63}, left (Fig. 6). Miner's rule predicted 282 cycles.

On the other hand, subjecting a set of assemblies to 220 cycles in 25–75C (50% of life) we found 66% of life remaining in subsequent 0–100C cycling (Fig. 7).

0–100C cycling did, as said, represent an extreme high strain case for these assemblies. Combining instead the two slightly less extreme conditions we do, however, find the same trend. Cycling to 50% of life in 25–75C, like before, and then to failure in 0–75C we find a remaining life of 144 cycles, or 91% of the characteristic life (Fig. 8).

Table 1 summarizes the above results.

4. Discussion

Consequences of the above trends obviously depend on the approach taken to interpret accelerated test results. Thermal cycling results are commonly extrapolated to service conditions using Fi-

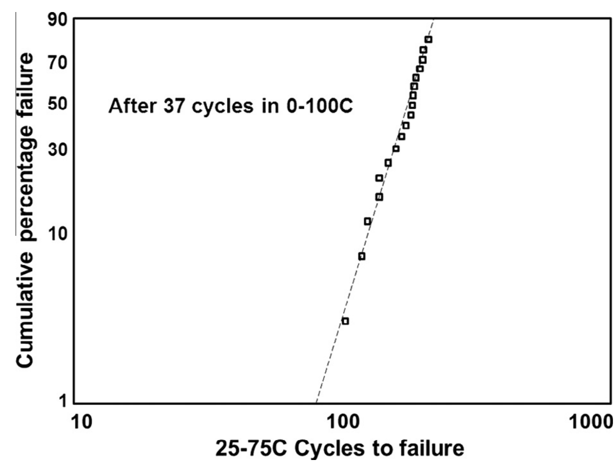

Fig. 6. Cumulative failure distribution for thermal cycling of ultra-fine pitch WL-CSP assemblies between 25 °C and 75 °C after first having been 'pre-damaged' by 37 cycles from 0 °C to 100 °C.

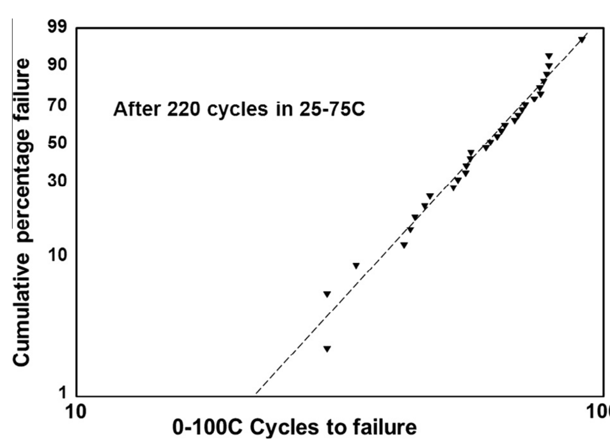

Fig. 7. Cumulative failure distribution for thermal cycling of ultra-fine pitch WL-CSP assemblies between 0 °C and 100 °C after first having been 'pre-damaged' by 220 cycles from 25 °C to 75 °C.

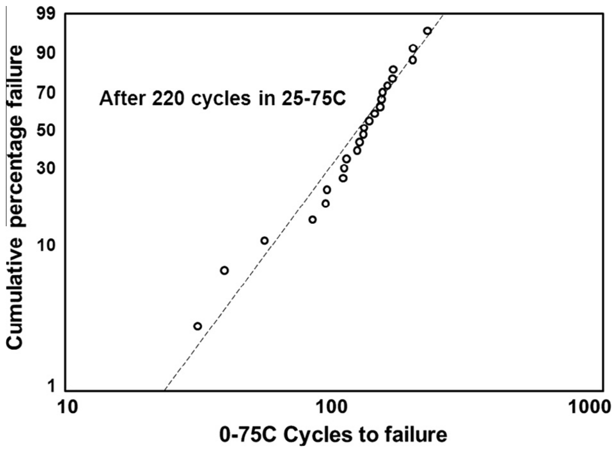

Fig. 8. Cumulative failure distribution for thermal cycling of ultra-fine pitch WL-CSP assemblies between 0 °C and 75 °C after first having been 'pre-damaged' by 220 cycles from 25 °C to 75 °C.

Table 1
Characteristic life, N_{63}, in different thermal cycles with or without preceding cycling with different temperature ranges.

Preceding				37@0/100C	220@25/75C	220@25/75C
Final	0/100C	0/75C	25/75C	25/75C	0/100C	0/75C
N_{63}	101	159	449	188	66	144

nite Element Modeling (FEM) to calculate stresses and strains vs. time while assuming a damage function of these or parameters calculated from them to predict the rate of damage per cycle. Failure under conditions of isothermal vibration, on the other hand, is most often addressed in a highly accelerated random vibration test while extrapolations to life in service may be based on a simple *S–N* curve. At present neither approach is capable of accounting properly for realistic amplitude variations.

4.1. Thermal cycling

FEM requires the assumption of constitutive relations the most complicated of which are those for the solder [7]. Temperature and strain enhanced coarsening of the secondary precipitates lead to ongoing and often dramatic changes in creep properties [8]. We can account for this through the use of microstructurally adaptive constitutive relations [7], albeit at great cost in terms of computing time. The effect of amplitude variations is, however, associated with the damage function. Failure in thermal cycling occurs by recrystallization of the Sn and crack growth along the resulting high angle grain boundaries [9–13]. The damage and failure rate controlling mechanism is the formation of a complete network of grain boundaries across the high strain region of the joint [14]. A forthcoming publication will show that this varies with the low temperature stress, with the maximum temperature in the cycle and the dwell time there, and with the average spacing of the secondary precipitates. High-Ag joints do, for example, not recrystallize easily until after some coarsening. The 'critical' precipitate spacing above which recrystallization becomes effective is greater for lower stresses [14,15].

A step-down in cycling range (say, from 0–100C to 25–75C) was shown to lead to less of an increase in remaining life than predicted based on Miner's rule of linear damage accumulation, while a step-up led to less decrease than predicted. In general, the rate of damage accumulation in a given thermal cycle is thus affected by the conditions in preceding cycles. This behavior is consistent with recrystallization in the milder cycles being more sensitive to precipitate spacing [14,15], so that the rate increases more as the precipitates coarsen in cycling. In comparison, the rate of recrystallization varies less with precipitate coarsening in harsher cycling. Based on this we predict similar trends for lower-Ag alloys, but here recrystallization starts out easier [14,15] so the sensitivity to variations in cycling temperatures is expected to be weaker.

4.2. Isothermal cycling

Repeated drops, cyclic bending and accelerated vibration testing of assemblies often lead to failure by solder pad cratering or through the intermetallic bond (IMC) to one of the pads, rather than through the solder itself. Depending on materials and design parameters IMC failure tends to dominate at very high load amplitudes, cratering at intermediate ones, and solder failure at very low amplitudes and strain rates [6].

In contrast to failure in thermal cycling solder failure in isothermal cycling occurs by transgranular crack growth [16]. Previous work on high-Ag joints showed the brief exposure to a higher cycling amplitude to have lasting effects on the solder properties in subsequent milder cycling [2]. Repeated excursions to a higher amplitude led to further, partially permanent, softening of the solder, and thus to faster damage at the lower amplitude as well [4]. This was ascribed to effects of amplitude on the dislocation cell structures and explains the breakdown of Miner's rule, as the rate of damage scales with the work [15].

Denoting the relative increase in work per cycle at a low amplitude due to '*i*' interruptions by a set of high amplitude cycles as $f(i)$ this provides for a modification of Miner's rule for solder failure [4]:

$$1 = \sum_{i=0}^{s} \left\{ f(i)\frac{n_{lo}}{N_{lo}} + \frac{n_{hi}}{N_{hi}} \right\} \tag{2}$$

where s is the total number of mild-harsh sequences (12–24 MPa in Figs. 3a and 3b). $f(i)$ depends on the amplitudes and is seen to increase with s, while it is much less sensitive to the number of harsh cycles in each sequence. Work is ongoing to generalize this to combinations of more amplitudes, but it seems clear that the effect of mild cycling on subsequent damage in harsher cycles remains negligible.

This has obvious consequences for our interpretation of accelerated vibration test results in terms of life in service. The observed trends suggest that life under random vibration conditions that include a few near-resonance cycles may be particularly sensitive to the time sequence. It may also have consequences for comparisons between alloys and/or process conditions. A forthcoming publication will show the alloys and microstructures that are most resistant to fatigue in cycling with a fixed amplitude to also be the ones for which the fatigue life may be reduced the most by the kind of amplitude variations possible in actual service.

The situation is even more complicated as far as solder pad cratering is concerned. Not only do amplitude variations affect the solder properties, and thus the stresses on the pad, damage accumulation in the laminate is also not linear. Most critically, the relative effect of a given high load increases as the low amplitude is reduced, i.e. accelerated testing tends to underestimate subsequent effects of latent defects induced, for example, in testing or handling.

4.3. Combinations

The most general service conditions involve combinations of thermal excursions and isothermal loading. Effects of combinations have been demonstrated [17–19] but systematic work is required before these observations can be generalized or 'worst case scenarios' identified. Subjecting regular area array assemblies to mechanical shock loading before thermal cycling was found to enhance the risk of a cross over to pad cratering failure [5]. In fact, we generally ascribe the ever more frequent observation of pad cratering failures in thermal cycling to preceding damage in assembly, testing or handling.

As far as solder failures are concerned we would expect a 'worst' combination to be a significant amount of thermal cycling followed by vibration [20], while the opposite would be much less damaging.

5. Conclusions

Significant progress has been made towards an understanding that will allow us to devise better accelerated tests and interpret the results in terms of long term life under realistic service conditions. However, more systematic work is clearly needed.

Combinations of thermal excursions and isothermal loading may lead to cross over between competing failure modes. Even if we focus on a particular failure mode, the number of cycles to failure may be strongly affected by such combinations or 'just' variations in cycling amplitude.

In isothermal cycling the worst case would involve *repeated* variations between one or a few harsh cycles and a larger number of milder ones. This reduces the solder fatigue life much more than the exposure to same total number of harsh cycles at one time.

In thermal cycling the life is much shorter if the harsher cycling precedes the milder cycling than the other way around. However, in this case we expect effects of repeated alternations between harsh and milder cycling to 'average out' to a larger extent.

A given product may of course face a broad and often not very well defined range of practical service conditions, and meaningful reliability assessments should focus on 'worst case scenarios' within this range. Systematic trends are emerging that will help identify such scenarios for inclusion in testing. Indications are that the higher-Ag alloys, which tend to be more fatigue resistant, are also more sensitive to variations. A concern is that they may prove inferior in a 'worst case scenario'.

Mechanical shocks that might occur in assembly, test, environmental stress screening or subsequent handling are often included as preconditioning in accelerated testing, but changes in acceleration factors need to be assessed as well.

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