Effects of Varying Amplitudes on the Fatigue Life of Lead Free Solder Joints

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Abstract

Realistic manufacturing, test, handling and service conditions tend to involve significant variations in loading of microelectronics assemblies. However, assessments of reliability are commonly based on accelerated cycling tests with fixed amplitudes and effects of variations are estimated assuming a damage accumulation rule such as Miner's rule. These rules may overestimate the life of lead free solder joints under realistic conditions by orders of magnitude. The severity of such errors is not likely to be captured in accelerated testing with combinations of amplitudes selected at random or based on convenience.

Brief exposure to one or more high strain rate loading cycles may significantly reduce the effective stiffness of typical lead free solder joints in subsequent cycling at lower amplitudes and strain rates. This may greatly complicate modeling and generalization of test results whether failure occurs through the solder or the intermetallic bond to the contact pad, or by pad cratering. Systematic studies of individual SAC305 joints in isothermal fatigue led to an approach to the determination of 'worst case' scenarios and the prediction of effects of amplitude variations on solder failure. Preliminary results on lower-Ag alloys and the MaxRel™ alloy are presented as well.

Introduction

The most common, and certainly most accurate, assessments of the long term fatigue life of microelectronics interconnects are based on accelerated cycling together with a careful interpretation of the test results. In contrast, so-called 'engineering tests' are not usually intended to lead to a quantitative prediction of life in service, but even they rely on the assumption that the assembly that performs best in test will also do best in service. Both these tests and those aimed at a quantitative life assessment do, however, miss potentially important effects by maintaining a constant cycling amplitude in a given test. Realistic long term service conditions can rarely be approximated by that.

Useful quantitative life predictions almost invariably rely on the, at least implicit, assumption of a damage accumulation rule to account for variations in amplitude. It is not commonly recognized that comparisons or rankings of alternatives in 'engineering tests' may be affected by variations as well. Thus, for example, a common mode of failure in isothermal cycling of assemblies is solder pad cratering. Not only did systematic testing show the number of cycles to failure by cratering to be reduced by invisible 'pre-damage' induced by shock loading, the acceleration factor (slope of the S-N curve) was reduced as well [1]. Importantly, the reduction in acceleration factor varied with laminate which might affect a ranking of materials in terms of life in long term service (much lower amplitudes). Initial 'shock' loads were also found to reduce the acceleration factor for solder fatigue failure in isothermal cycling [2].

According to Miner's rule [3] a solder joint will 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. Thus, for example, cycling of an assembly to 10% of the number of cycles to failure under one condition ('consuming 10% of the total life') is expected to leave a remaining life of 90% under any other cycling condition. Needless to say this first of all requires that the failure mode is the same under any of the conditions. It does, however, also require the rate controlling damage ***mechanism*** to be the same. It is therefore not surprising that Miner's rule breaks down for SnAgCu solder joints in sequences of, for example, thermal cycling and vibration [4] even if the joints fail by crack growth through the solder in all cases.

We have also shown Miner's and other common damage accumulation rules to break down even if we just vary the amplitude in isothermal cycling. The remaining life of a SAC305 joint after a change in amplitude was, for example, found to easily end up 5-10x lower than predicted by Miner's rule [2,5-7]. Figure 1 shows an example where a step-down in amplitude left a remaining life in cycling that was 11x lower than predicted [5].

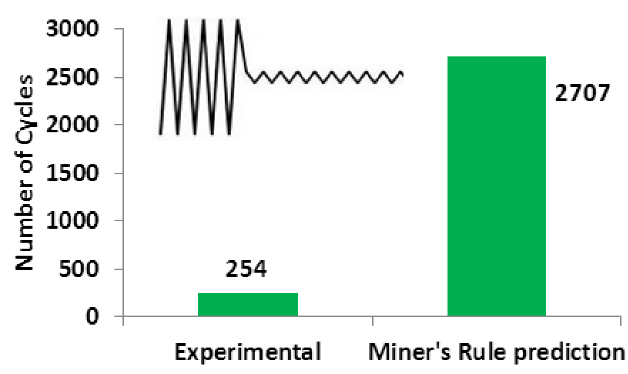

Fig. 1: Remaining characteristic life in shear fatigue cycling with 230gf amplitude after consuming 60% of life in cycling with 400gf amplitude – experiment and prediction [5].

This is of obvious potential concern for assessment of life under realistic service conditions. To make matters worse, deviations from Miner's rule depend strongly on the specific sequence of amplitudes and number of cycles for each. Testing with a few combinations of amplitudes chosen at random is, therefore, not likely to reflect the typical magnitude of such effects. Generalization of results will require a systematic understanding.

We have shown the observed deviations from the above mentioned damage accumulation rules to be results of 'memory effects' as far as important solder properties are concerned [6]. There appears to be a general tendency for a brief increase in cycling amplitude to lead not only to damage by itself but also to a permanent increase in the rate of damage accumulation in subsequent cycling after returning to a lower amplitude. Based on this we have proposed [7], and continue to improve on, a practical approach to the assessment of life in shear, bending or vibration of assemblies with various combinations of amplitudes.

Below, we shall illustrate how our current level of understanding may be sufficient to identify the 'worst' combination of two cycling amplitudes for a given application. This not only allows for better quantitative estimates of worst case life under realistic service conditions, it may also prove essential for the interpretation of routine 'engineering tests' comparing alternative materials, designs or processes. We finally present and discuss preliminary results on effects of solder alloy and strain rates.

Experimental

Systematic insights and understanding were enabled through isothermal shear fatigue experiments on individual solder joints. Solder bumps on pads were cycled individually in an Instron micromechanical tester, allowing the ongoing monitoring of the load-displacement loops and thus the calculation of work and effective stiffness for each. Figure 2 shows top and side view sketches of the shear fatigue fixture and how it makes contact with a joint. The first few cycles lead to significant, but still limited, flattening of the joint in the areas of contact, the 'equator', but after that shear stresses and deformation are concentrated in a region just above the pad surface [8].

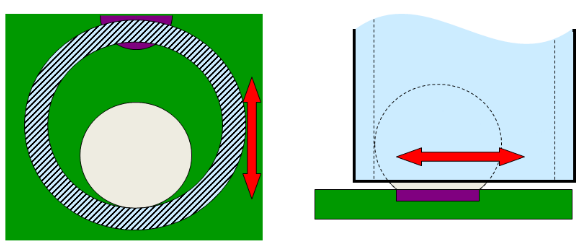

Fig. 2: Schematics showing top and side views of how the hollow cylinder contacts an individual solder joint in cycling.

30 mil (0.75mm) diameter spheres of 4 different solder alloys (Table 1) were reflow soldered onto 22 mil (0.55mm) diameter copper pads on typical BGA component substrates. The MaxRel alloy was only available as 24 mil (0.6mm) diameter spheres. Soldering these to the same size pads led to bumps with a lower 'equator' and the lower height of contact with the tool led to less torque on the joint. The size of the 'stress concentration' region was, however, not changed so the nominal shear stress there remained similar. Nevertheless, for purposes of comparisons we need to keep in mind that life time values were affected to a currently unknown degree.

Alloy	Diameter	Composition
SAC305	30mil	3.0%Ag, 0.5%Cu
SAC105	30mil	1.0%Ag, 0.5%Cu
SAC(Ni)	30mil	1.2%Ag, 0.5%Cu, 0.05%Ni
SACX-plus	30mil	0.3%Ag, 0.7%Cu, 0.05%Ni, 0.08%Bi
MaxRel	24mil	3.6%Ag, 0.75%Cu, 0.1%Ni, 2.8%Bi, 1.5%Sb

Soldering was accomplished by first printing a tacky flux through a stencil onto the substrate pads and then placing individual spheres through apertures in a separate 'bumping' stencil. 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 and 45-60 seconds above liquidus.

Figure 3 shows examples of load-displacement loops for SAC305 joints cycled with two different amplitudes. The initial slope of the curve as the load increases from zero offers an empirical measure of the 'effective stiffness' of the joint in the plane of loading. The inelastic energy deposition (work) in the cycle was assessed from the area enclosed within the loop.

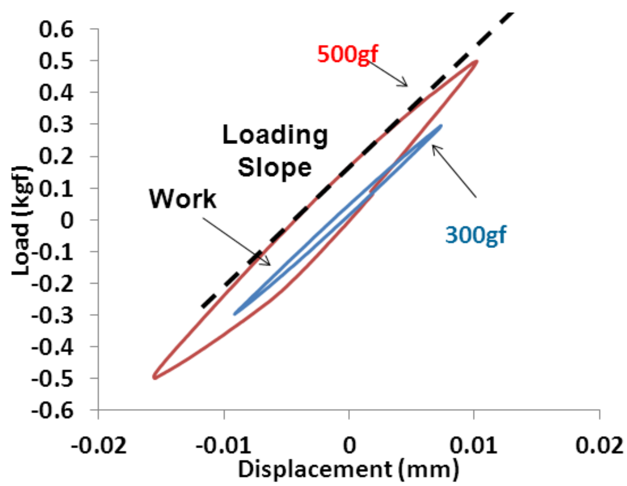

Fig. 3: Load vs. displacement for SAC305 joint cycled with two different amplitudes, 300gf and 500gf.

Materials Behavior in Cycling

Figure 4 shows a typical example of the evolution of the effective stiffness of a MaxRel joint in load controlled cycling with a fixed amplitude of 700gf. The initial rise reflects a combination of flattening and hardening of the joint, after which the dislocation cell structure remains stable and the stiffness almost constant until the onset of measurable crack growth [9].

Both the initial stiffness value and the steady state level vary strongly from joint to joint, reflecting the well-established variability of solder joint properties. This is primarily a result of the apparently random orientations of the few (or single) highly anisotropic Sn grains in each joint relative to the loading direction [10]. Smaller, but still significant, variations are undoubtedly caused by differences in the secondary precipitate distributions associated among other with variations in degree of undercooling in cool-down from reflow. Nevertheless, sufficient numbers of replications helped reveal a systematic trend.

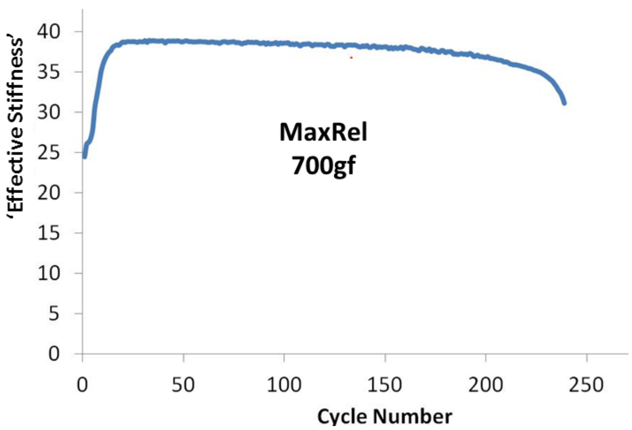

Fig. 4: Effective stiffness (initial loading slope) vs. cycle number in load controlled cycling of MaxRel joint with fixed 700gf amplitude.

Not surprisingly, the initial hardening tended to occur faster for higher loading amplitudes, but this still lead to the establishment of lower steady state stiffnesses. Figure 5 shows average stiffnesses vs. cycling amplitude for four of the alloys. The SAC105 results were indistinguishable from those for SAC(Ni). The actual values for the MaxRel are undoubtedly affected by the lower contact point of the shear tool, but the much lower sensitivity to the amplitude is still significant. We also note that SAC305 seems to be slightly more sensitive to the amplitude than the lower-Ag alloys.

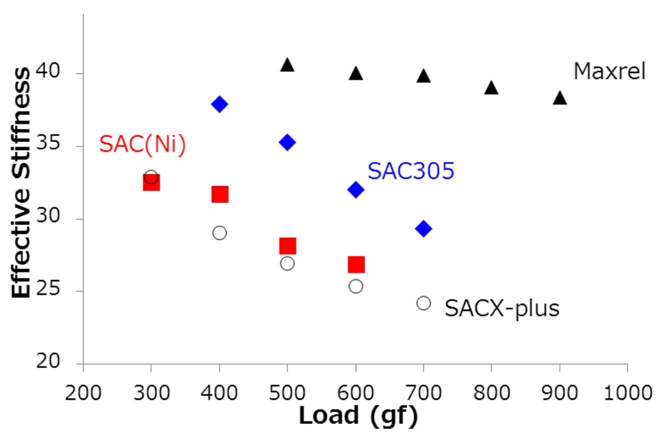

Fig. 5: Effective stiffness after hardening vs. fixed cycling amplitude for Maxrel, SAC305, SAC(Ni) and SACX-plus joints.

The dependence of the stiffness on amplitude together with the long term durability of the stiffness established by hardening at a given amplitude may help explain the observed break-down of common damage accumulation rules. It is for example an obvious requirement of Miner's rule that the important materials properties are the same, after the consumption of a given fraction of the total life, no matter what the loading history involved was [2, 8]. This requirement is not met by the present lead free solder alloys.

Figure 6 shows the effective stiffness as a function of cycle number for a particular SAC(Ni) joint cycled with an amplitude of 300gf. After every 50 cycles the amplitude was raised to 600gf in a set of 7 cycles, leading to a reduction in the stiffness. Considering the trends in Figure 5 it is of course not surprising that a change in amplitude leads to changes in the dislocation cell structure. However, this effect is not reversible when returning to a lower amplitude from a higher one (Fig. 6), i.e. the stiffness remains lower than it would have been without the excursions to 600gf. This provides for a 'memory' effect that explains why Miner's rule must break down.

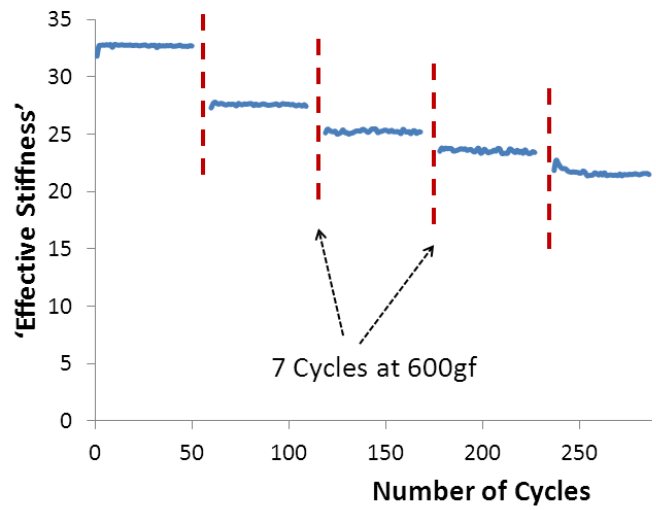

Fig. 6: Effective stiffness of SAC(Ni) joint in cycling with 300gf amplitude. After each set of 50 such cycles, the joint was subjected to 7 cycles with 600gf amplitude (stiffness not shown).

Comprehensive studies to be published elsewhere provided for a systematic picture of the effects of the high and low amplitudes, as well as the number of cycles at each, on the effective stiffness. Further complicating the picture preliminary results showed the effect of the higher amplitude cycles on the subsequent stiffness at the lower amplitude to depend on the strain rates. Indications are that reducing ***both*** the nominal strain rates from an estimated 0.3 s^{-1} to about 0.03 s^{-1} would reduce the 'memory' effect significantly, but the same was not the case if the strain rate was kept high in the high amplitude cycles. Studies are ongoing to cast further light on this.

An important consequence of all this is that Finite Element Modeling of isothermal cycling with varying amplitudes may be seriously misleading until we learn to predict the evolution of the constitutive relations reflected in the 'memory' effect.

Damage Accumulation in Solder

The effective stiffness as measured is determined by the combination of the elastic modulus and the strain rate dependent load relaxation (creep) during loading. The variations in Figure 6 therefore reflect general changes in the creep properties. These have consequences for the associated damage accumulation.

Figure 7 shows the evolution of the inelastic energy deposition (work) per cycle corresponding to the effective stiffness in Figure 4, for a MaxRel joint cycled with a fixed amplitude of 700gf. The initial hardening leads to a strong drop in the work per cycle, after which it remains essentially constant until crack initiation and failure.

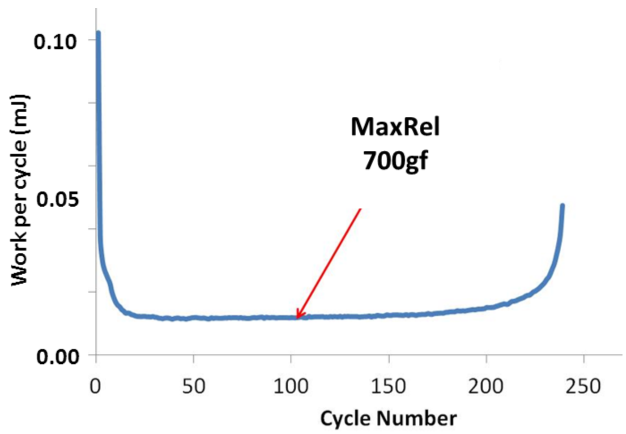

Fig. 7: Work per cycle in load controlled cycling of MaxRel joint with fixed 700gf amplitude (corresponding to Fig. 4).

Qasaimeh [9] showed the failure of 30 mil diameter SAC305 solder joints to occur upon the accumulation of approximately 25mJ, independently of amplitude. A forthcoming paper shows how this is only an approximation, albeit a reasonable one for practical purposes and one that applies for variable amplitudes and a wide range of strain rates.

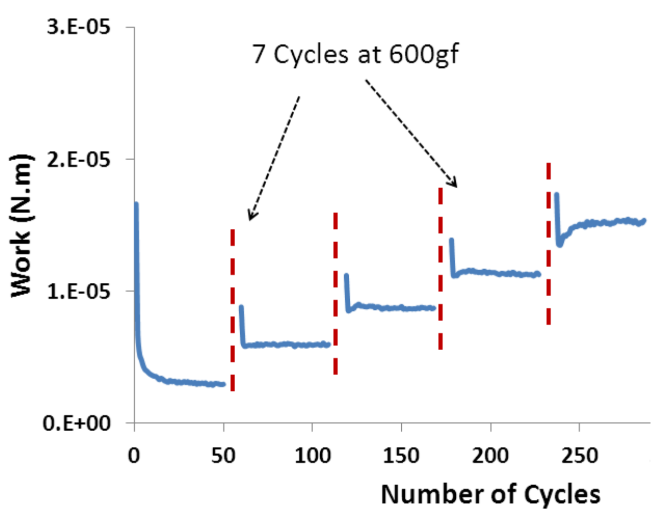

Fig. 8: Work per cycle in load controlled cycling of SAC(Ni) joint with 300gf amplitude. After each set of 50 such cycles, the joint was subjected to 7 cycles with 600gf amplitude (work not shown). Same experiment as in Fig. 6.

This provides a quantitative explanation for the observation of a shorter remaining life, after a step-down in amplitude, than predicted by Miner's rule [2, 5-7]. The changes in effective stiffness in Figure 6, for example, reflect very large changes in creep properties and thus in the corresponding work per cycle (Figure 8). In this case the work per 300gf cycle was almost doubled after exposure to 7 cycles with 600gf, and later excursions to 600gf led to further increases. The reverse effect of the milder cycling on work per cycle at the higher amplitude, on the other hand, was negligible. As the work per cycle offers a relative measure of the rate of damage evolution the resulting reductions in remaining life are therefore readily calculated [7].

We define an amplification factor, α, as the relative increase in work per cycle at the lower amplitude after exposure to a set of higher amplitude cycles [7]. The overall amplification is seen to increase with the number of times we return for another set of high amplitude cycles (Fig. 8). The same is true for any other combination of two amplitudes [7].

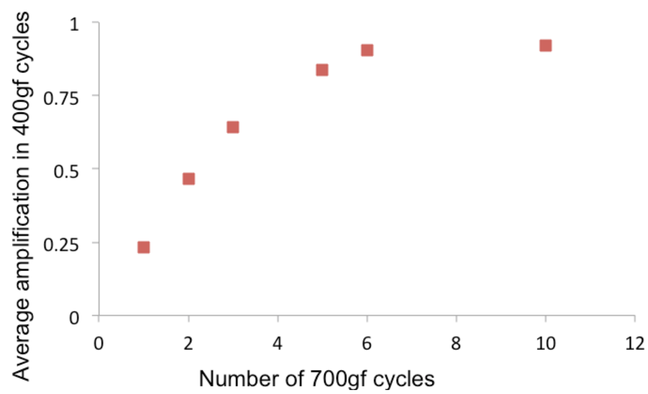

Fig. 9: Average amplification factor for work per cycle at 400gf when interrupted once by a given number (n_{hi}) of 700gf cycles.

Figure 9 shows the average amplification factor for cycling at 400gf when interrupted by a single set of 700gf cycles. α is seen to increase with the number of 700gf cycles in the set, but it soon levels off. Interestingly, however, repeated exposure to shorts sets of 700gf cycles, in between cycling at 400gf, had a much stronger effect on the total amplification than a correspondingly longer single set of 700gf cycles. Thus, the amplification after two sets of five 700gf cycles is about twice as large as the amplification after one set of ten such cycles. In fact, the amplification is generally found to increase approximately linearly with the number of times we return for another set of the same high amplitude cycles [7]. This allows for the definition of a 'modified Miner's rule':

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

where

$$f(i) = 1 + i \bullet \alpha$$

is the relative amplification of the work per cycle at the low amplitude after 'i' sets of n_{hi} cycles at the high amplitude [7].

Although α varies with n_{hi} for small values of n_{hi} (Fig. 9), this damage accumulation rule allows us to predict life under any combination of two given amplitudes based on testing of only a few combinations. Accounting for the greater amplification in the first few cycles after return from the higher amplitude (Fig. 8) complicates predictions slightly, but the general approach remains the same.

Comprehensive studies to be published elsewhere revealed the systematic effects of amplitudes and numbers of cycles at each amplitude, and work is ongoing to address the effects of strain rates. Completion of this phase of our studies should allow us to predict the life for any combination of any two amplitudes. Generalization to more than two amplitudes will be the subject of future work.

Practical Use and Consequences

The potential practical use of the present and ongoing work ranges from general insight and identification of concerns to the definition of test protocols and means of generalizing test results. The following offers only a brief outline and illustration of this.

Accelerated isothermal vibration and cyclic bending tests more often lead to solder pad cratering or failure of the intermetallic bonds than to failure through the solder. Whatever the failure mode, however, the rigidity of the solder must clearly affect the load on pad and intermetallic bonds in an assembly. A conventional S-N curve for the failure mode in question may account empirically for the effect of cycling amplitude on the solder stiffness, but it does not account for effects of amplitude variations ('memory') on the stiffness. This may be further complicated by softening of the board (and the component?). Single sided cyclic bend testing often leads to a permanent deformation of the board, believed to be associated with global microcracking. We would expect double sided bending and vibration with sufficiently large amplitudes to lead to effective softening of the board as well. These effects are counteracted by local effects of the excursions to high amplitudes on damage evolution in the intermetallic layers or the laminate under the pads. Load controlled testing of individual pads, eliminating effects of solder stiffness and compliance of the board, showed exposure to one or two high amplitude cycles to reduce not only the subsequent cratering life in milder cycling but also the associated acceleration factors [1]. Quantitative interpretations and generalization of cratering results, not to mention extrapolation to long term life at lower amplitudes, would have to account for all of this.

Depending on the quality of the intermetallic bonds and laminate material, as well as the overall design, solder fatigue failures become dominant at sufficiently low strain rates. This may for example be the case for long term service life limited by relatively mild but ongoing vibration.

When it comes to solder failure the extension of our approach to applications of more direct relevance, vibration or cyclic bending of assemblies of components on printed circuit boards, is of course complicated by our inability to measure the work per cycle, and thus amplification factors, for the individual joints. However, this problem can be circumvented by appropriate use of our modified Miner's rule [7]. Still, it becomes critical to also account for potential 'softening' of the printed circuit board and/or the component as mentioned above. In the following we shall focus on illustrating general trends based on our shear test results.

Focusing on solder damage preliminary results suggested that reducing the nominal strain rates on the solder from an estimated 0.3 s^{-1} to about 0.03 s^{-1} would reduce the 'memory' effect on the effective solder stiffness, and thus on the work amplification factor, significantly. However, this was only the case if the strain rate was reduced at both the high and the low cycling amplitude. Interruption of mild vibration by a few shock cycles is still expected to lead to a significant amplification of the subsequent work. It remains to be assessed how large would be the effect of ongoing vibration hitting a resonance on relatively rare occasions.

Realistic service conditions may vary greatly for different samples of a given product. Reliability assessments (and warranties) therefore commonly focus on a 'worst case' scenario. Possible amplitudes obviously depend on the specific product and its intended uses. Possible combinations of these amplitudes may be limited, but we focus here on the worst one possible.

The question then arises as to what is the worst combination of the amplitudes. So far, we need to limit this to combinations of only two amplitudes, but the answer still offers significantly more realistic assessments of a 'worst case scenario' than current practices relying on fixed amplitude life values and Miner's rule. For present purposes we define 'worst' in terms of error in the life predicted based on Miner's rule. The CDI (Eq. 1) would be the relevant measure of error when attempting to account for ongoing variations in amplitude through the life of the product. The error in terms of something practical, such as total years of life (specified in the warranty?), does however have to be calculated from this. On the other hand, environmental stress screening (ESS) does for example rely on the assumption that the damage induced in 'burn-in' reduces the ***remaining*** life of the product in service by less than 5-10%. The remaining life at a fixed amplitude may not always be the most relevant but it is a much more intuitive measure.

Keeping in mind that variations only really affect damage at the milder amplitude it is clear that any total life estimate for which cycling at the higher amplitude accounts for, say, 60% of life is going to lead to an error of less than 40% in terms of damage ratios or CDI. Figure 1 shows that the error in the ***remaining*** life can be very large, but the CDI is still 0.64. However, once we have consumed 60% of the characteristic life we approach commonly expected uncertainties in life predictions anyway. The greatest error in CDI ***and*** in remaining life of actual concern is encountered in cases where cycling at the higher amplitude accounts for less than 10-20% of the total life. Furthermore, Miner's rule only underestimates the damage at the low amplitude ***after*** amplification. Thus, an ***initial*** shock load causes a greater overall error than the same shock would if occurring after some amount of mild cycling. For purposes of illustration we therefore consider a 'worst case' scenario in which the amplitude is varied during the first 20% of the ***predicted*** life (based on Miner's rule) and assess the effect on the remaining life at a fixed low amplitude. In this case the CDI also provides an intuitive measure of the remaining life.

Considering first the effect of an initial shock load, and assuming that we attempt to account for this based on Miner's rule, experiments show that the work amplification factor at a given lower amplitude increases strongly with the amplitude of the shock load. On the other hand, as argued, the worst error in our life estimate is encountered when the shock consumes 10-20% or less of the total life. Of course considering the statistical variations in SnAgCu solder joint properties we would not want to allow for shocks so large that the ***typical*** joint would not survive at least 5-10 of these anyway.

As reflected in our modified Miner's rule repeated returns to high amplitudes in between low amplitude cycling cause more amplification. To which extent more returns to a lower amplitude cause more amplification than a single excursion to a higher one depends on how fast α increases with the amplitude. As illustrated in Figure 9 two or more high amplitude cycles in a set lead to a larger α than one, but the increase is slower than linear. On the other hand, fewer returns to longer sets of high amplitude cycles lead to less damage in the milder cycles in between. It is thus in fact not immediately obvious what will be the worst combination, but we expect it to involve very short sets of high amplitude cycles.

For a start, we consider combinations of 400gf and a higher amplitude. As documented in detail in a forthcoming publication the worst combination was found to be alternation between 10 cycles at 400gf and 2 cycles at 600gf, repeating this sequence 16 times. In spite of ongoing amplification of work in the 400gf cycles the actual damage accumulated in this stage was dominated by the 600gf cycles. After that, Miner's rule predicted a remaining life of 80% but the actual remaining life at 400gf was only 11.5% (CDI=0.315). This minimum was not very sharp, 18 sequences of 10 cycles at 400gf and 3 cycles at 550gf leaving us with only 11.7% life remaining at 400gf.

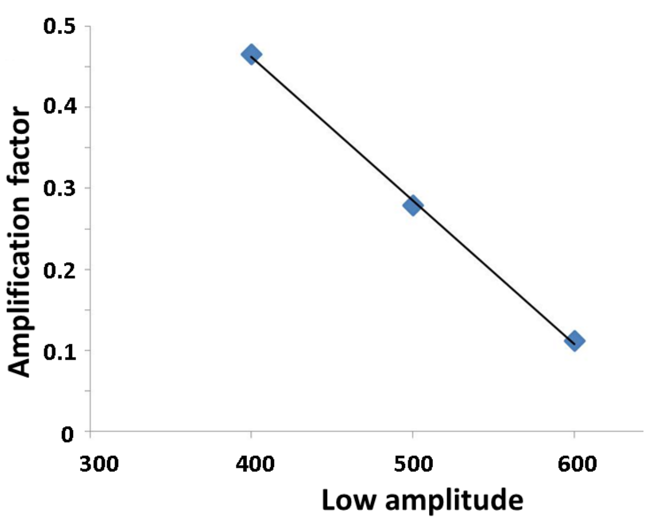

Fig. 10: Average amplification factor for work per cycle at different low cycling amplitudes when interrupted by 2 cycles at 700gf.

Of course 400gf, which corresponds to a nominal shear stress of about 16MPa, is not a low amplitude of concern for long term service. Not surprisingly the amplification of work due to a given set of high amplitude cycles increases strongly as the low amplitude is reduced. Figure 10 shows the amplification factor for different low amplitudes interrupted by 2 cycles at 700gf. This is consistent with the original observation that a couple of initial 'shock' loads would reduce the subsequent ***acceleration factor*** for solder fatigue failure in isothermal cycling [2]. This trend is similar to what was observed for cratering [1], but the reasons for the latter are expected to be somewhat different.

Thus, predictions of the effect of an initial exposure to 16 sets of 2 cycles at 600gf (24MPa) on the remaining life at a low amplitude of relevance to long term service based on Miner's rule would be expected to be in error by more than an order of magnitude. Work is in progress to assess the apparent acceleration factor after such 'preconditioning'.

Further work is required to understand effects of, among other, strain rates. The 'worst case scenario' identified may not be realistic for most applications, but the above approach is readily adapted to other ranges of combinations.

Work is currently ongoing to assess whether different sensitivities to amplitude variations may affect the ranking of the current alloys and others in terms of performance under realistic isothermal cycling conditions. Figure 5 suggests that SAC305 may be particularly sensitive to amplitude as far as effective stiffness is concerned, with the lower-Ag alloys slightly less so and the MaxRel possibly much less. However, 'memory effects' were observed for all of them.

Figure 11 shows less amplification for sequences of 50 cycles at 400gf and 2 cycles at 600gf than for SAC305, but this is unlikely to be the worst combination for SAC105.

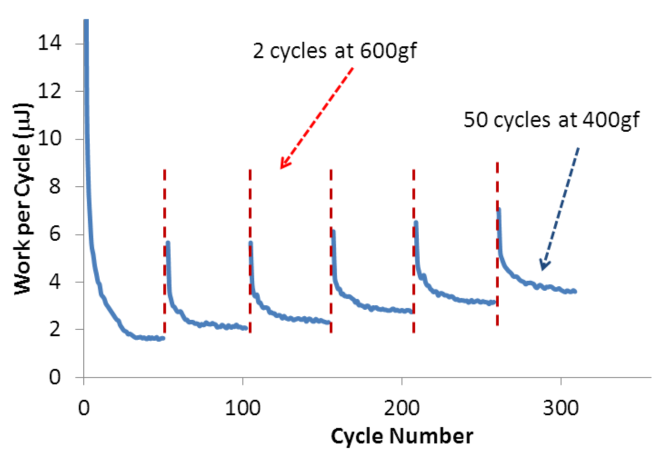

Fig. 11: Work per cycle in load controlled cycling of SAC105 joint with 400gf amplitude. After each set of 50 such cycles, the joint was subjected to 2 cycles with 600gf amplitude (work not shown).

Preliminary results on MaxRel also show amplification (Fig. 12), but it remains to be ascertained whether the reductions in stiffness, and thus the amplified work per cycle, survive ongoing cycling at the lower load as they did for SAC305. Even if so, the worst combination for this alloy is certain to be very different.

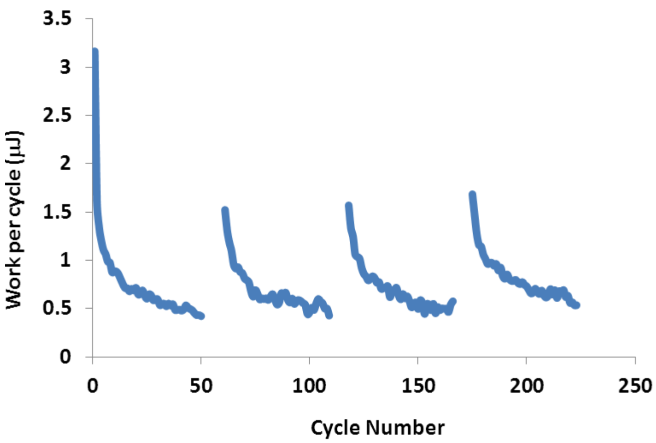

Fig. 12: Work per cycle in load controlled cycling of MaxRel joint with 600gf amplitude. After each set of 50 such cycles, the joint was subjected to 5 cycles with 800gf amplitude (work not shown).

Conclusions

Variations in cycling amplitude may lead to significant, permanent changes in the rigidity of lead free solder joints. Calculations based on current constitutive relations may thus lead to serious errors in terms of stresses, strains, and work done on solder, intermetallic bonds and the laminate under the contact pads.

Predictions based on Miner's rule may overestimate the remaining life in service after exposure to a few high strain rate events by more than an order of magnitude. A 'worst case' example for SAC305 joints may be repeated sequences of loads on the order of 20MPa during early stages of life. Significant effects are also expected for SAC105, SAC(Ni), SACX-plus and the MaxRel alloy, but corresponding worst case conditions for these remain to be determined. Work is ongoing to assess effects of higher amplitudes with lower strain rates.

The present work relied on shear fatigue testing of individual solder joints to show how to identify the 'worst' combination of two cycling amplitudes for a given application. This approach is readily extended to vibration or cyclic bending of assemblies of components on printed circuit boards [7]. Accelerated tests may, however, here easily be complicated by cycling induced 'softening' of the printed circuit board and/or component.

Acknowledgments

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