

REPORT

Influence of Rework Conditions on Microstructure in Tin-Lead Solder Joints

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August 1999

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ABSTRACT:

A survey recently carried out by the SSTC established that there is a wide range of rework conditions used in the electronics manufacture industry. However, the impact of this variation on microstructure and joint reliability has not previously been characterised. This work establishes the impact on microstructure when varying the rework temperature and duration of the soldering operation. Assemblies manufactured under the various rework conditions were also thermally cycled to assess the impact on reliability. The high homologous temperature of the solder and rapid restoration processes that take place in solder tend to minimise the impact of varying the rework conditions.

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ISSN 1361-4061

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

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1. INTRODUCTION

A recent survey of rework practices of the UK Electronics Assembly Industry has been conducted by the National Physical Laboratory ⁽¹⁾. This study outlined the need for a better understanding of the effects of rework practice on the reliability of solder joints. The survey revealed that companies often do not control soldering temperatures, application times, or background heating. It was also found that few companies followed component manufacturers' recommendations aimed at preventing damage to thermally sensitive components. The impact of this widespread variation in rework conditions is investigated in this paper, the outcome of which forms the basis of recommendations on rework temperatures and times from a solder joint reliability perspective.

The results from the survey formed a basis for a matrix of various combinations of temperature of the iron tip and the application time to a surface mount assembly rework joint. Solidification parameters of time, peak temperature and hence cooling rate, have a significant effect on the microstructure of a metal. This study investigated whether such effects taking place during the solidification of a solder joint could be fatigue life critical.

The binary eutectic alloy 60%Sn40%Pb commonly used in electronics manufacture was used in this study. Eutectic alloys can solidify in one of two ways depending on the cooling rate and consequently the degree of supercooling. This cooling also affects the microstructure of the eutectic phase. The eutectic or $\alpha + \beta$ phase can form as either alternate plates of α and β lamellae, or rods of α in a surrounding β phase. This is a result of a thermodynamic phenomenon which requires a maximum entropy of fusion and therefore a minimum interfacial energy. This will be dependent upon the volume fraction of each element remaining in the liquid upon the formation of the eutectic solid ⁽²⁾. The closer to equilibrium the cooling conditions are, the higher the likelihood of formation of lamellae and vice versa. Under rework conditions cooling rates are relatively high and solder joints will almost certainly form as a rod structure, though this structure itself has variations and lamella characteristics can be seen in areas of those joints formed at the bottom of the soldering energy scale. As cooling rates increase further, the supercooling will also increase which corresponds to a finer microstructural matrix due to preferential nuclei formation as opposed to nuclei growth. Therefore a high dispersion of fine α rods in β is more energetically favourable than a coarser dispersion of larger rods in the matrix ⁽³⁾. Measurements of inter-rod spacing will enable monitoring of this transformation through the testing conditions.

As soldering is essentially the joining of two surfaces, the alloy will come into contact with a copper interface on the printed circuit board (PCB) pad, and in the case of ceramic chip components, the nickel of the barrier layer on the component. The nickel layer on the component is known as a barrier layer, and is used to prevent leaching of silver from the underlying component termination into the solder. The dissolution of copper in solder is appreciable as can be seen in Figure 1, and intermetallic compounds are formed rapidly at the joint pad interface. This process is temperature dependent, and therefore it is expected that the level of copper in the solder joint will vary with different soldering conditions.

The formation and growth of intermetallic precipitates has a direct influence on the microstructure of the joint; it will change the composition of the solder ahead of the

solidification interface by depletion of the constituent which participates in the formation of intermetallic. Intermetallic formation will cause the depletion of tin around the intermetallic and will create a lead rich layer ahead of the growth interface. This can result in a high degree of phase heterogeneity within the solder joint if the density of such intermetallic is high. This investigation explored the effect of various levels of intermetallic formation during soldering.

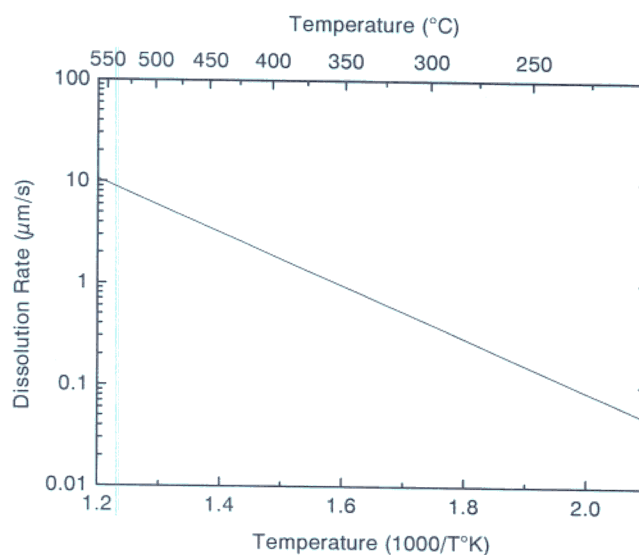


Figure 1 Dissolution of copper in SnPb solder

Theoretically, according to Figure 1, the investigation can expect to reveal dissolution levels of between approximately 1 and 40 μm , the latter being a huge figure. In reality this is expected not to be the case, for as saturation levels are approached the dissolution rate will decline as the solute solubility limit is reached. Upon cooling, the levels of copper solute in the melt will exceed the solubility limit and further intermetallic will be precipitated. It is for this reason that large levels of intermetallic compounds are expected to be present throughout the joint fillet.

This study investigated the correlation of microstructural data with mechanical and fatigue life testing to identify the optimum combination of soldering iron tip temperature and application time.

2. EXPERIMENTAL

A single sided surface mount FR4 152 x 152mm board with a hot air solder levelled finish and resist coating was used. Mounted on each board were 35 x 2512 1K Ω resistors and 35 x 0805 47K Ω resistors. The components were arranged in groups of five in alternate vertical / horizontal orientation. One board was manufactured for each of the twenty rework conditions identified below. Five boards were manufactured for study at zero cycles containing six components for each condition. Each component was soldered using an MTA Automated Soldering robot allowing each rework condition to be adhered to accurately.

Results from the survey of rework practice revealed that it is essential to consider temperatures up to 425°C and application times of up to 20 seconds. The matrix of conditions shown in Table 1, were the ones used to manufacture the assemblies and cover those typically used in industry with examples of both low and high energy extremes. The blank cells in Table 1 correspond to conditions that were not used in manufacture. This range of conditions was expected to produce the variations in microstructure discussed earlier. A short time and low temperature are referred to as producing a low energy joint whereas a high temperature and a long time are referred to as producing a high energy joint. In Figure 2 the degree of shading is proportional to the energy input to the joint, and is simply the product of time and temperature.

Table 1 Number of boards manufactured with each set of soldering parameters

Soldering Time	Temperature(°C)			
	275	325	375	425
2	0	0	1	1
4	1	1	1	1
6	1	1	1	1
10	1	1	1	1
20	1	1	1	0
30	1	1	1	0

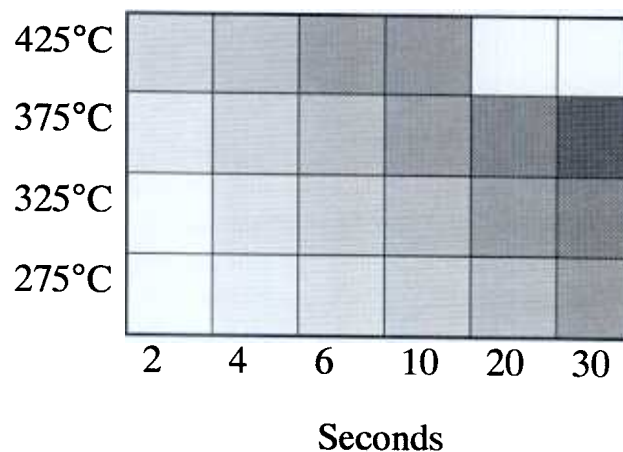


Figure 2 Illustration of relative energy input into each solder joint

Twenty of these boards, each representing one condition, were then thermally cycled. A thermal cycling chamber was operated for 1000 cycles of -20°C to 100°C at a ramp rate of 10 °C/min. Liquid nitrogen was used as the coolant gas. Two boards were used for microstructural examination. The remaining three were used for mechanical shear testing immediately after manufacture. Following 1000 thermal cycles the 20 boards were subjected to the same examination of microstructure and mechanical testing. Microstructural data recorded were inter-rod spacing of the eutectic, and intermetallic layer thickness.

Boards undergoing thermal cycling were removed from the chamber for electrical continuity measurement. The resistance was measured at intervals of approximately 250 cycles. The fail criterion was when the resistance fell outside the 5% tolerance of the resistor.

Metallographic preparation was performed on a Struers Abramatic machine using a standard polishing route for SnPb solders. Subsequent examination and microstructural measurements took place on a Leica Microscope using KS400 image analysis software.

Mechanical testing was carried out using a Farco shear testing instrument. The load was applied in the plane of the board so as to replicate the stress applied to the solder joint during thermal expansion of the component as shown in Figure three. To achieve this components were carefully slit in half with a diamond saw. Components were stressed to failure and the ultimate shear strength recorded.

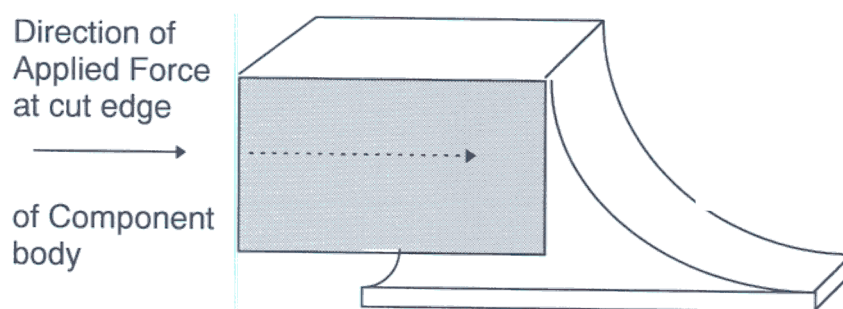


Figure 3 Shear testing method

3. RESULTS

After 1000 cycles no electrical failures were recorded for any of the components. Therefore all experimental observations were recorded from components which hypothetically would still have been in service. Any defects in the solder joints potentially affecting the resistors will be identical in both the 0805 and the 2512 devices, although the effects will be greater in the 2512's, as the larger physical dimensions will increase the effect of the thermal mismatch between the component and the board. For this reason all the measurements considered in the analysis are for the 2512 resistors.

3.1 INTERMETALLIC LAYER MEASUREMENTS

As expected the layer of intermetallic growth at the interface between the pad and the joint increased with time and temperature as can be seen in Figure 4. Thicknesses ranged from approximately $0.2\mu\text{m}$ for low energy input joint to $5.2\mu\text{m}$ for highest energy input.

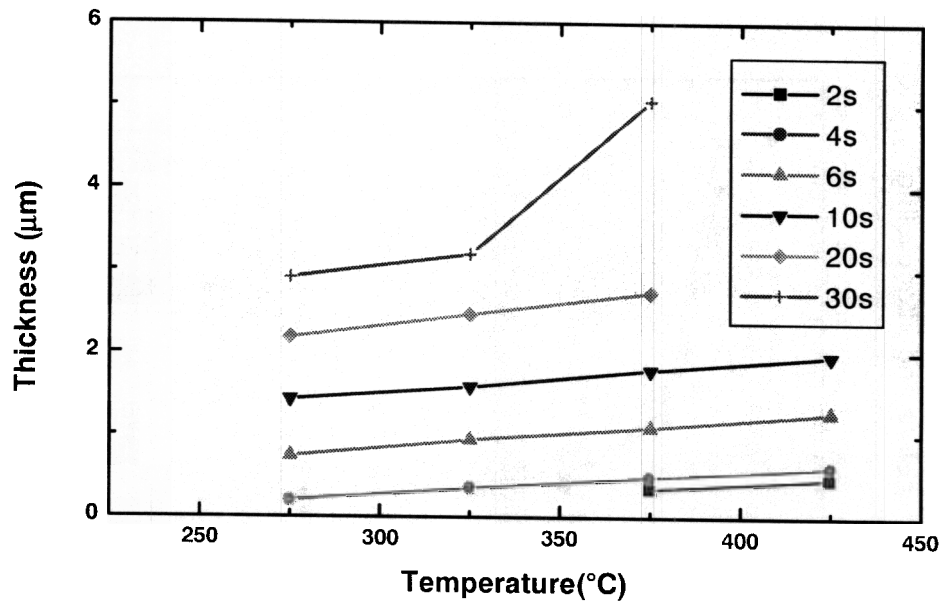


Figure 4 Intermetallic layer thickness at zero cycles

Figure 4 shows the intermetallic thickness which formed at the interface between the PCB pad and joint. The results indicate that the increase in intermetallic thickness with respect to temperature is almost linear. A similar increase with respect to time is also observed, with the exception of that between 2 and 4 seconds.

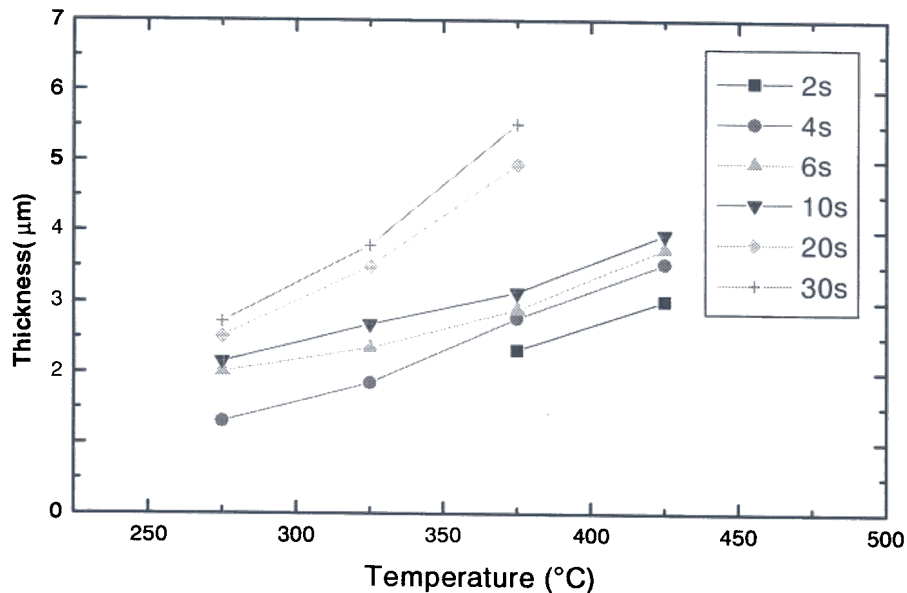


Figure 5 Intermetallic thickness at 1049 cycles

In Figure 5 it can be seen from the measurements, that the intermetallic thickness does increase with cycling, confirming the growth of intermetallic compounds in the solid state.

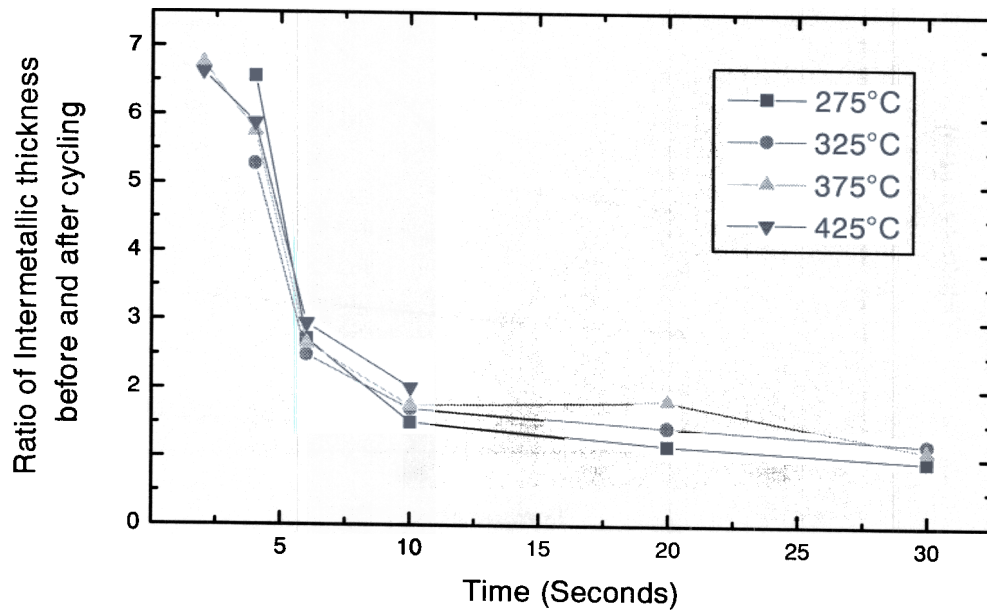


Figure 6 Ratio of intermetallic thickness before & after 1049 cycles

Figure 6 describes the increase in thickness of the intermetallic layer at the interface between the PCB pad and the solder joint after 1049 cycles. This is presented in the form of a ratio of the thickness at zero cycles to the thickness at 1049 cycles. The results highlight a significant contrast between the two energy extremes, although this difference is defined only by the time of application and appears independent of temperature. Ratios of as high as five and six for two and four seconds application time rapidly decline to approximately two after 10 seconds. Subsequently, this the ratio tends to 1 as the application time increases.

This behaviour implies that using shorter application times, which results in relatively low levels of growth in the liquid state, a high level of growth potential remains in the material, that can be realised over time in the solid state. Alternatively, if longer application times are applied, then it is evident that greater growth is achieved in the liquid state, the ratio tending to a maximum at around ten seconds. This higher level of growth in the liquid state appears to exhaust all growth potential as a further increase of intermetallic material is not seen after the solder has solidified.

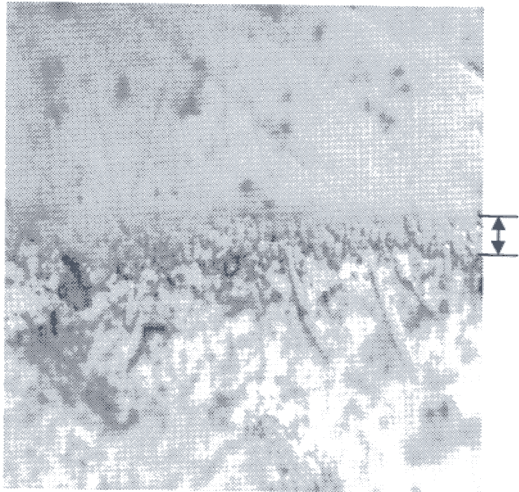


Figure 7 Intermetallic layer at 0 Cycles (160x)

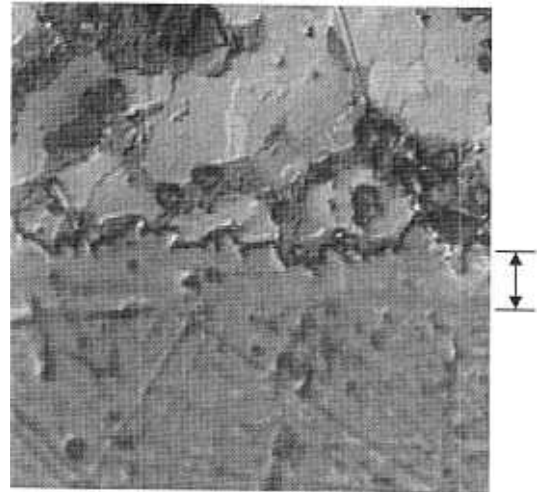


Figure 8 Intermetallic layer at 1049 cycles (160x)

Figures 7 and 8 show clearly the difference in appearance of the intermetallic at the interface between the bulk solder and the PCB pad before and after cycling (The increase in thickness is illustrated by the indicator to the right of each Figure). The high density of fine needle-like crystals present at zero cycles has given way to a less dense population of coarser shape.

3.2 EUTECTIC INTER-ROD SPACING MEASUREMENTS

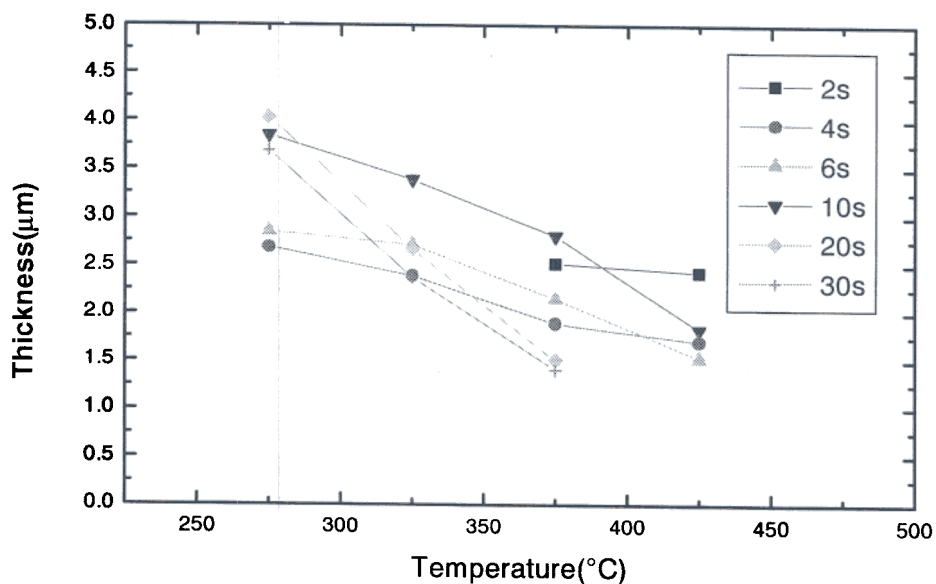


Figure 9 Inter-rod spacing versus temperature for all application times

In Figure 9, measurements of eutectic inter-rod spacing illustrate clearly the gradual increase in the density of finer alpha rods in beta phase. These measurements could not be carried out on the aged samples as the eutectic colonies coalesced to form grains of individual phases. This will be discussed later.

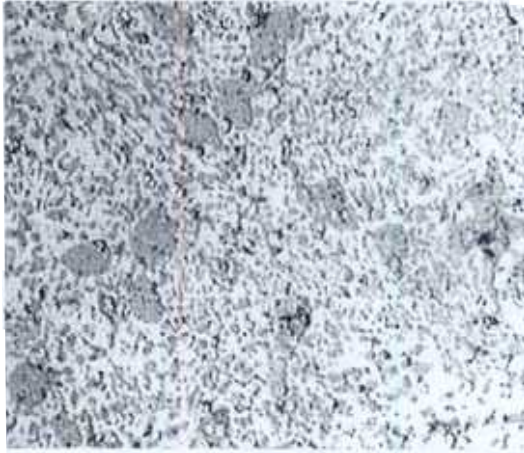


Figure 10 Low energy input joint (250x)

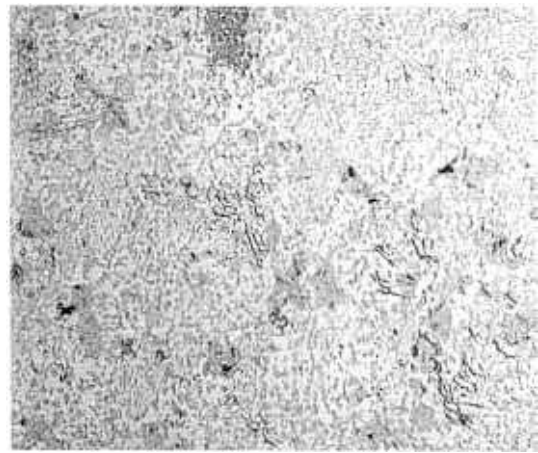


Figure 11 High energy input joint (250x)

Figures 10 and 11 illustrate the difference in the size of the eutectic structures. Figure 10 shows the appearance of large lead-rich alpha dendrites, which appear as dark regions surrounded by a coarse dispersion of alpha rods (dark spots) in beta phase (light area). Figure 11 shows the contrasting structure of a finer dispersion of alpha eutectic rods in beta phase. Also visible in Figure 11 are precipitates of intermetallic, which appear randomly, that appear in the joint at such high temperatures.

3.3 SHEAR STRENGTH TESTING

In Figure 12 force displacement curves with an arbitrary origin are shown for the rupture of solder joints. It can be seen that at zero cycles, there is a significant difference between the high energy input joints with a higher ultimate shear strength than those manufactured with low energy input. This observation reinforces the evidence that a high energy soldering input into a joint will create a different joint to a lower energy soldering input. The joints which have been aged for 1049 cycles do not show the same difference in characteristics, although the data for the high input energy joint suggest a slightly stiffer joint. This behaviour correlates with the microstructural changes that occur under soldering and thermal cycling.

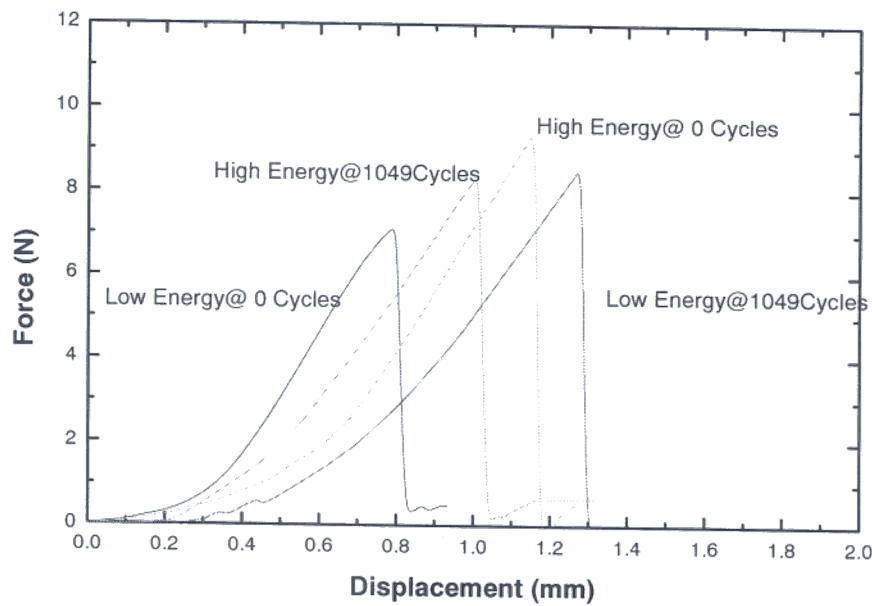


Figure 12 Shear strength curves for high and low energy joints before and after 1049 cycles

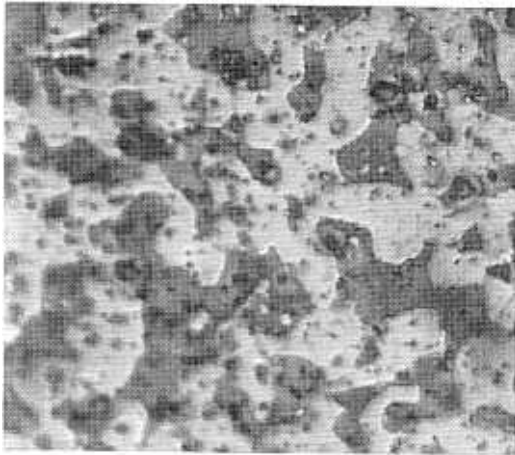


Figure 14 Low energy after 1049 cycles (160x)

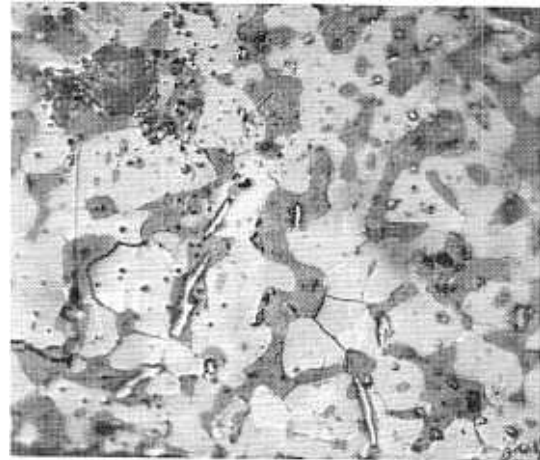


Figure 13 High energy after 1049 cycles (160x)

In Figures 13 and 14 the microstructure is shown after thermal cycling for both the low and high energy joints. These micrographs can be compared with those in Figures 10 and 11 before cycling. Figures 13 and 14 show that the eutectic has homogenised, such that the two joints appear identical in this respect. However, it can be seen that the large precipitates of intermetallic are completely unchanged by the thermal cycling.

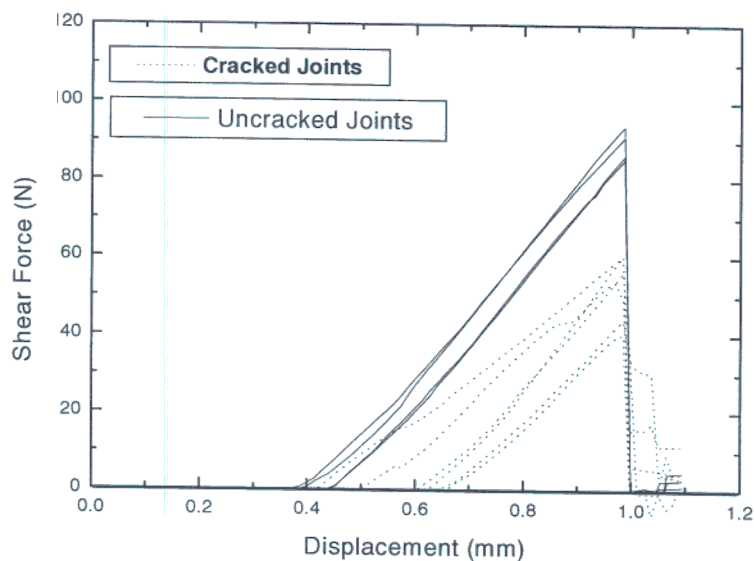


Figure 15 Shear tests on cracked and undamaged high energy joints after 1049 cycles

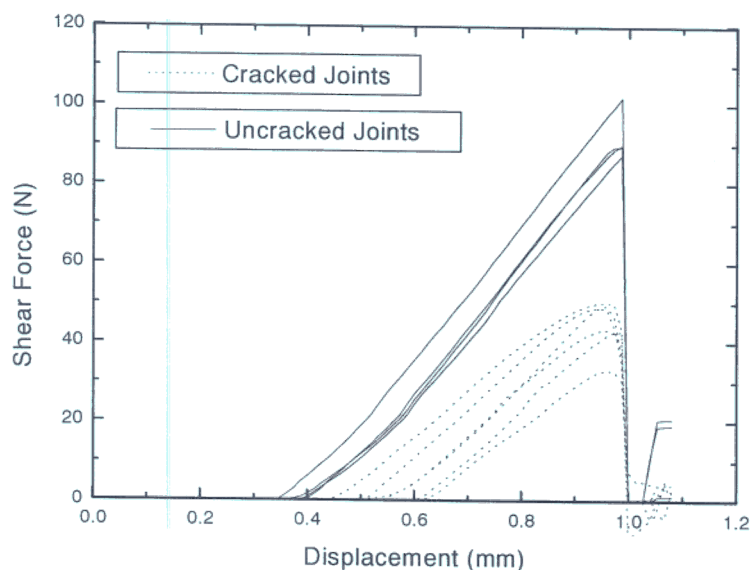


Figure 16 Shear tests on cracked and undamaged low energy joints after 1049 cycles

In Figures 15 and 16 individual force displacement curves are shown after thermal cycling. In each Figure the results are partitioned between the fatigue cracked (dashed lines) and the uncracked (solid lines) solder joints. This classification refers to how the two solder joints for a single resistor degrade during thermal cycling. As the thermally induced stress is applied in repetitive cycles, one joint suffers greater damage, with consequent crack initiation. This joint will then preferentially absorb all the stress leaving the other relatively undamaged. Hence

randomly testing solder joints will reveal two populations of the cracked and the uncracked joints. In Figures 15 and 16 there is little difference between the results for the uncracked joints. The high energy cracked joints in Figure 15 show higher strength and a more brittle fracture than their low energy counterparts in Figure 16. The low energy cracked joints in Figure 16, following the yield point, show plastic deformation before complete failure.

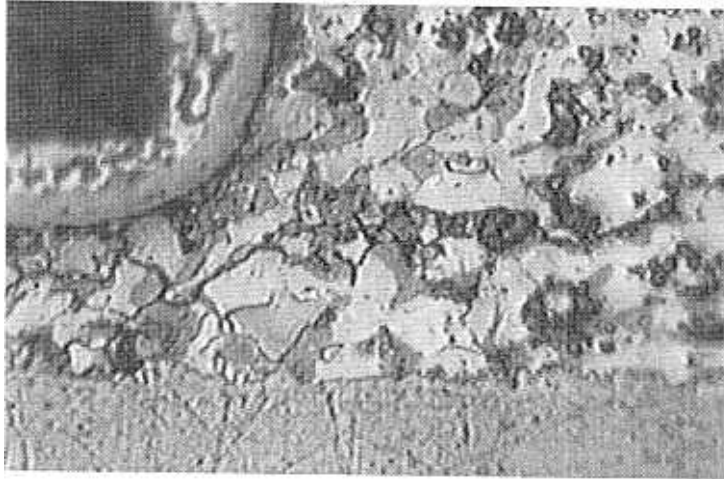


**Figure 17 Cracking in a high energy rework joint
(75x)**

In Figure 17 a cross section of the corner of a resistor after thermal cycling is shown. This is for a high energy rework joint and the coarse grain structure is again noted. This section of the joint is the region of highest stress, and cracks are observed in this region first. Intergranular cracks are present.

4. DISCUSSION

Although there were no electrical failures of components that had been cycled, extensive examination of cross-sectioned joints did reveal severe microstructural damage. The shear strength testing also showed that the mechanical strength of the joint had deteriorated.

The microstructural examinations yielded the most useful information. Differences in initial microstructure between different soldering conditions could be related to the shear strength data.

The effect of over 1000 thermal cycles was profound for all soldering conditions. The examination of intermetallic compounds forming at the interface between board and pad has confirmed that the thickness of this layer is directly related to iron tip temperature and application time. It can be noted from Figure 1 that the dissolution of copper in SnPb is directly related to temperature and therefore it was expected that this pattern would be observed. More interesting is the pattern shown in Figure 5 which indicates a further increase in the thickness of these compounds after the specimen have been aged.

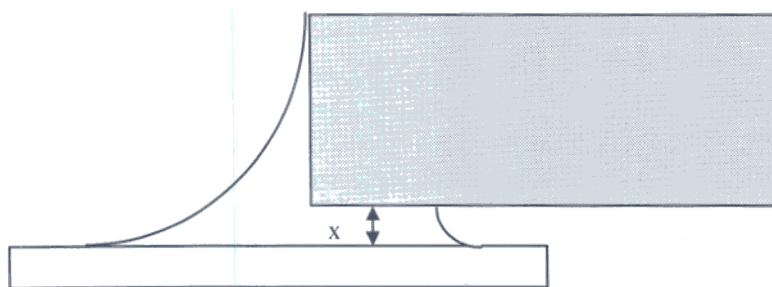


Figure 18 Illustration of stand-off height

Figure 18 describes the nature of solder joint between a surface mount resistor and a copper pad. This diagram illustrates that the two surfaces are in close proximity to each other (distance x , in Figure 18) especially under rework conditions in which components are manually paced on the board, a process involving variable amounts of pressure.

Solder easily wets between the narrow gap. As it does so, it immediately begins to form an intermetallic compound between the joint and copper pad, and also with the nickel barrier layer on the component. As these compounds form in the liquid state, the tin from the solder is replaced by diffusion of metal from the bulk of the solder joint. Thus upon solidification there is a sufficient bond of SnPb eutectic layer between a Cu_6Sn_5 layer at the pad and a Ni_3Sn_4 at the component termination. If however growth of either of these compounds continues after solidification, then Sn from the eutectic will be consumed in the intermetallic reactions. As diffusion in the solid state is slow the eutectic will become depleted of tin. Therefore as these structures age further, the region between the interface will be populated almost entirely by a lead-rich alpha phase, which is a softer material. The trend in intermetallic growth in the solid state described in Figure 6 shows that growth of this kind, although appreciable within some conditions, is of negligible proportions when using application times of more than ten seconds. Therefore, this is an effect that can be monitored. Further investigation is required to clarify the role of tin depletion in this part of the joint and the impact on reliability.

The above discussion illustrates how two different microstructural processes can interact and how that interaction may be detrimental to the overall performance of the alloy.

It is evident from the microstructural examinations, that the eutectic colonies present in joints manufactured at high and low energy inputs respectively are, as expected, contrasting in their main characteristics. These contrasting characteristics are thermodynamically unstable and hence are transformed by thermal cycling. Low cooling rates produce microstructures containing primary lead-rich alpha phase dendrites, surrounded by relatively coarse rod-like structures in which lamella characteristics can be noted. Higher cooling rates produce a more dense dispersion of fine rod structures. After 1049 cycles these initial microstructures have homogenised. The colonies of eutectics have given way to an even distribution of equiaxed alpha and beta phase grains regardless of the initial microstructures. This is due to the high homologous temperature, T_h , the ratio of actual temperature to melting point. At 100°C , the peak temperature of the cycling regime, the homologous temperature will be approx. 0.82 (and indeed at room temperature it is approximately 0.65)⁽⁴⁾. This explains the high level of initial microstructural instability and it is easily understood that under these conditions, through diffusional restoration processes, the metal will always be able to find its lowest energy state. For eutectic SnPb this state is the equiaxed grain structure observed in Figures 13

and 14. This correlates with the shear testing data which also show marked change in the material properties subsequent to the thermal cycling. Observation of these results show a stark comparison of ultimate shear stress between rework conditions. Before cycling the high energy joints are noticeably stronger than the low energy joints due to the fine microstructure present in those joints. The different mechanical properties of the initial contrasting structures present prior to cycling, have, subsequent to homogenisation, developed properties characteristic of midway between the two. Therefore the theory of homogenisation is given credence by data indicating that both the mechanical and the microstructural properties are the same for joints which are manufactured at either high and low energy levels. Although conventional microstructural theory suggests that it will take those joints which have been cooled rapidly (and hence have a finer eutectic structure) a longer period of time to reach that state. The findings of this investigation suggest that this time difference is surpassed by 1049 cycles.

Examination of the curves in Figures 15 and 16 for cracked joints indicate a difference not in ultimate shear stress but in the failure characteristics. The high energy joint fails with a sharp peak, describing brittle fracture. Whereas the low energy joints fail with a curved peak suggesting a more ductile fracture.

5. CONCLUSIONS

This investigation has shown that differences in overall reliability resulting from different rework conditions are not marked. Hence arrange of rework conditions can be tolerated. The most pertinent microstructural issue involved in rework soldering is the dissolution of copper into SnPb eutectic. This copper forms intermetallic compounds at the interface between the board and the pad, and for high temperatures and long duration soldering operations, these same compounds are dispersed throughout the body of the joint.

The thickness of the intermetallic layer is directly related to temperature and the time of which this temperature is maintained. Therefore to obtain an ideal level of this intermetallic these parameters must be optimised.

The objective for optimisation of rework parameters should be to obtain continuity of process by creating rework joints that exhibit similar microstructural properties to conventionally reflowed joints. It is generally accepted that for a typical reflow profile the thickness of an intermetallic layer between pad and joint would be approximately 0.5µm. Therefore, in order obtain a rework joint with the closest comparison to a reflow joint in terms of intermetallic layer thickness, a soldering iron should be applied to a surface mount rework joint at a temperature of 375°C for four seconds. However the eutectic microstructure of the body of a reflow joint cannot be replicated using a soldering iron due to the nature of the process. Hence these parameter values have been chosen as a compromise between long application time, which will produce a slower cooling rate, and higher temperature, which will allow adequate but not excessive intermetallic levels.

Different cooling rates have been found to produce great differences in the microstructure of the eutectic body of the joints. However, these differences are gradually eliminated as the solder is aged. This is due to a high homologous temperature which gives rise to an

unstable microstructure which is easily able to achieve its lowest energy state; equiaxed grains of alpha and beta phase. Classical microstructural theory would suggest that the time for this elimination to take place will be longer for those joints having finer structured colonies of eutectic. This process was not monitored in this investigation as cross-sectioned joints were only examined after 1049 cycles by which point all joints had achieved this microstructure.

The fatigue performance across the range of rework conditions was not marked. As highlighted above, the homogenisation of the microstructure has a normalising effect on the strength. Subtle differences did remain between the two rework extremes, of which the most obvious is the relative volume of the intermetallic phase. The high energy rework condition has a memory of the soldering conditions, with the thicker intermetallic layers at the board and the component interface, and dispersed intermetallic precipitates. A possible consequence of this for the high energy solder joints, is that directly underneath the component and above the pad, the growth of the intermetallic layers will deplete the eutectic solder of tin. Hence this lead-rich, and therefore soft, region, combined with the higher initial microstructural damage, will shed more of the thermally induced stress on to the outer part of the fillet and hence may shorten life.

The shear testing results for joints formed at high temperatures with long application times have a marginally higher ultimate shear stress and therefore are stronger. However this strong behaviour is only exhibited for a finite period of time before homogenisation (during ageing and thermal cycling of the joint) eliminates the structures within the alloy which exhibit this strength.

6. ACKNOWLEDGEMENTS

The work was carried out as part of a project in the Materials Measurements Which Affect Processability (MMP09) Programme of the UK Department of Trade and Industry. The authors are grateful for many useful discussions with Martin Wickham.

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