Predicting the Positive Effects of Combined Metallurgical and Thermo-Mechanical Impacts on the Reliability of Solder Joint Interconnections

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ABSTRACT

Generally speaking, solder joints fail due to both fatigue and creep. Therefore both mechanisms are strongly considered by designers and manufacturers as an important design criteria. However, since most designers take parameters individually, their designs are considered as an over design. The parameters considered in this study, which have a direct influence on fatigue life and creep individually, are grain direction, grain size, temperature, and yield strength. Obviously, most of these parameters have opposite dual effects on both the fatigue and creep mechanism. In other words, each parameter might have a positive effect on fatigue but also a negative effect on creep and vice versa. For this purpose, this study uses the metallurgical assumptions, and stress analysis theories, on the data present in literatures in order to characterise and determine the significance degree of each parameter, and also determine the overall effect on the solder life. This study recommends focusing on the combinability of the parameters that have significant effects on solder joints reliability in electronic interconnection, recognising the positive effects, and using them on the overall solder life. Such potential approach may assist in reducing the size and cost.

Keywords: solder joints, metallurgical aspects, creep fatigue failure, stress analysis, thermomechanical impact

1 INTRODUCTION

Solder joints, in electronic devices, is the most common application which met both fatigue-creep failure simultaneously [1-2]. During operation, the temperature is raised and then the solder joints exposed to thermomechanical fatigue TMF due to mismatching a coefficient of thermal expansion CTE between components, i.e. substrate, solder joints and silicon chips [3-10]. Therefore, the solder joints are exposed to thermal cycling stress, recrystallisation, creep deformation, crack initiation, crack growth, and failure.

Fully understanding of solder joint failures is requiring studies that take either creep [1,2] or fatigue [11-15] individually, and/or both together [16]. Although research approaches usually are created on the view that taking such effects individually would help increase the reliability, and/or safety factor of the solder joints; it is worth noting that a few parameters have a dual influences on the electronics life. For example, parameters such as grain size, temperature, etc, has a negative influence on one failure mechanism, the same parameter might have a positive action on another failure mechanism, and as a result it could increase the life of the solder joint, when they are acting together at the same time. Predicting such advantages, and characterising their effects qualitatively, and then quantitatively, might be useful for decreasing the material size, and avoiding an over-design [6-8]. Therefore, the noticeable lack of research which practising this area is the main idea behind this research.

2 EFFECT OF THE PARAMETERS

The parameters considered in this study, which have a direct influence on fatigue life σ_e and creep individually, are grain or loading direction, grain size, temperature, and yield strength σ_y. Obviously, most of these parameters might have dual effects on both the fatigue and creep mechanism.

2.1 Grain or Loading Direction

Essentially, the materials are built in atoms, atomic planes, grains, and multi grains. The atomic planes would take their positions randomly during solidification and recrystallisation processes. Accordingly, the loading direction on those planes has strong and direct influences on the stress values, according to stress analysis basics which is simply realised by Mohr circle [4,5,9,13,15-20]. Obviously, all forming and deformation processes are carried out by shear stresses, τ, which always occur by dislocation movements within sliding or climbing, when the loading direction is not normal on the atomic planes [18-20]. When the angle between loading direction and the atomic plane reaches 45^o, a value of τ would reach the maximum compared with all other possible angles. Therefore, many attempts [5,9] are carried out to study beneficial effects of making unidirectional grains, on the component life when they adapted with loading directions, to provide better fatigue and creep resistance.

2.2 Grain Size

Grain boundaries GB are important factor in determination the properties and life estimation of materials. In one side, GB's have a positive effect at low temperature applications, when they acting as barriers to restrict dislocation movements, and then increase yield strength σ_y, according to Hall-Patch equation [15,20];

$$\sigma_y = \sigma_o + \kappa\, d^{-1/2}\,, \qquad (1)$$

Where d is the grain size, measured as mean diameter, κ, and σ_o, are material constants.

While, in the other side, GB's have negative effects at high temperature applications, when they are acting as easy regions of atomic movements within the diffusion process, and eventually would lead to creep [1,2,4]. Mainly, GB sliding is the main creep mechanism [18]. However, applications when both mechanisms (fatigue and creep) are combined, the estimation of GB's on the overall life of a component would be complicated due to the interactions of the parameters with each other [3,11-13,19].

2.3 Temperature

Temperature also is between other parameters that has dual effects on component life. In one side, it speeds up the creep phenomenon by diffusion process. Creep behaviour is strongly temperature dependent, typically becoming important engineering considerations around 0.3 to 0.6 Tm, where Tm is the absolute melting temperature. Above about 0.6 TM, GB regions are thought to have lower shear strength than the grains themselves, probably due to the looser atomic packing at grain boundaries. High temperatures encourage sliding, and climbing within planes that include shear stresses. The mechanism of void formation involves GB sliding which occurs under the action of τ acting on the GB's [12,13,19].

In the other side, raising the temperature acts to decrease the hardness H, and σ_y, and increase the ductility$\in$, e.g. plastic zone size r_p during crack presence. According to fracture mechanic approaches, as the r_p increases, fracture toughness K_{IC} generally increases. In the other mean, as the σ_y decreases, the r_p generally increases, and then K_{IC} increase [11-14,20]. Therefore, that means briefly, increasing the temperature would increase K_{IC}. In addition to that, since K_{IC} depends on crack propagation rate da/dN, one should remember that the externally applied tensile stress σ_t leads to a reduction in cycles to failure, while compressive stress σ_c leads to an increase in cycles to failure [2].

3 BASIC THEORY AND MODELS

Since there are many variables that have affect on creep failure, such as cyclic strain rate [7,12], microstructural state and mechanical properties [6,13], grain size and orientation [4,5,9,16,17], strain rate and mean stress [12,13,19], recrystallization or softening phenomena [1,18], grain size [2,12], CTE mismatches [2,3,5,10]; the creep-fatigue mechanism is still not under full control and understanding. Many attempts have been carried out to estimate improving the reliability of solder joints [6-8]. However, it has been difficult to collect all these parameters and their interactions in one model without using advanced software. Building such software is always started with simple flowcharts which recognise and/or predict the effect of each parameter qualitatively on the total life. This study would try to show the way of starting such interactions and predictions between the four parameters are mentioned above.

Figure 1 shows the atomic planes and/or grain orientations have a great influence on type and values of applied stresses. The figure shows when a force F is normal on an atomic plane, i.e. $\theta = 0^o$, no τ would occur, and that helps to restrict the dislocation movements, via sliding or climb. However, when the atomic planes start inclinations with the loading direction, the amount of τ is increased till it reaches 45^o, where it is the highest value and equals 0.5 σ [4,5,9,13,15-19].

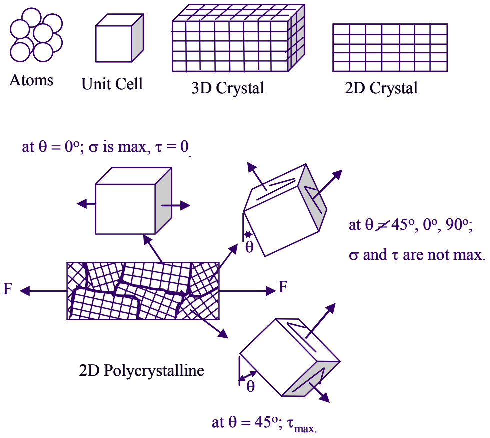

Figure 1: Effect of loading direction on type and values of stress.

In the other side, since GB's, at high temperatures, act as reasonable passes of atomic diffusion, cavity growth, and cavity coalescence interlinkage leading to fracture, small grains are preferable at low temperatures [4,5]. Moreover, since there are critical limits of deformation and temperature to cause recrystallisation or softening phenomenon, (see Fig. 2), these limits can be used to restrict recrystallisation, whenever required [20]. During the dwell periods, i.e. increasing and decreasing the thermal stresses due to heating and cooling the components, both strain hardening and stress relaxation would take place respectively. When such alternative stresses take place, that might lead to repair by recovery, recrystallization, crack healing, or additional crack growth from TMF residual stresses [2,3,5,9].

The same figure showed that both strain hardening and softening mechanisms dominate at high temperatures (high thermal stresses) and low temperatures (low thermal stresses) respectively [20]. At these temperatures there is a softening mechanism which works to soften the material by changing the microstructure. This is done mostly by recrystallization and growth of the new smaller grains into large grains. Creep is a balance between this softening mechanism and strain hardening caused by the strain itself. When these two are in balance, a steady state strain rate results [16-19]. In the other side, as mentioned before, K_{IC} generally increases with temperature. This change is much more considerable with materials that have a small number of slip systems; i.e. slip planes times slip directions. Data on the K versus temperature behavior of different solder joint alloys is useful in selecting specific compositions for service, as it is important to avoid high stress use of a material where its K_{IC} is low [11,14,20].

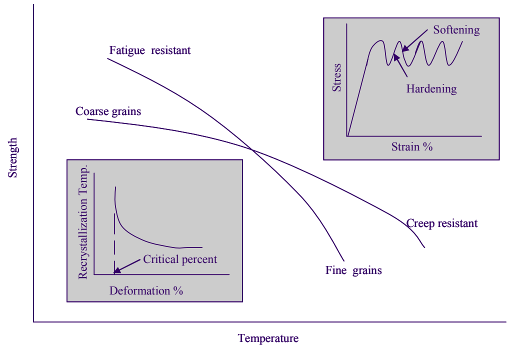

Figure 2: Effect of grain size on fatigue and creep resistant, with interconnecting the deformation and temperature on hardening and recrystallization.

Therefore, considering all these facts, combinability and quantitatively with the real variables, such as applied load direction, grain size directions, Tm of solder joints, working temperature, might help to increase the performance and life of solder joints.

4 PARAMETRIC STUDIES

To illustrate the micro-scale cyclic creep-fatigue damage model, a simple idealized test case is chosen. The configuration is shown in Figure 3. The figure consists of a thin layer of solder on a thick substrate. The substrate is assigned as higher CTE than solder and thus during a thermal cycle, σ_t will develop in the solder during heating and σ_c during cooling due to CTE mismatch [1-7,10].

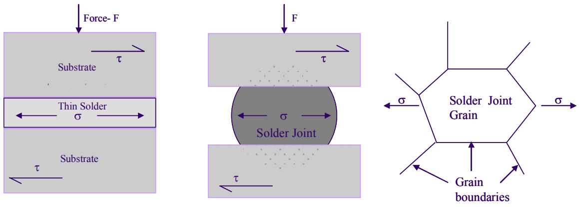

Figure 3: Schematic configuration of a solder joint under applied stresses and CTE mismatch.

As mentioned above, GB's and grain directions have a great influence on creep behaviour. Ding et al. [13] showed large angle boundaries would constrain grain rotation, and slip systems have difficulty to be started within partial grains. He showed that dislocations slip is hindered by obstacles such as grain boundaries, impurity particles, the stress field around solute atoms in solution or the strain fields of other dislocations. Generally speaking, creep ceases at temperatures lower than about 0.3 T_m. At high temperatures, dislocations gain a new degree of freedom; they can climb as well as slide. If a sliding dislocation is held up by discrete obstacles, e.g. GB's, a little climb may release it, allowing it to slide to the next set of obstacles where the process is repeated [18]. Fukutomi et al. [19] showed that the velocity of dislocations in the grain boundary is in proportion to the mean effective stress, and sliding rate reduced with stress dropping. Moreover, they showed that the rate of sliding gradually decreases with increasing time under constant stress.

In addition, high temperature enlarged grain size, and total area of GB's would decrease, consequently creep behaviour proceeds mainly along GB's would be limited [16]. Ding et al. [13] showed at higher temperatures, solder joints exhibit the creep behavior via GB sliding which may account for 10% to 65% of the total creep strain. This contribution is increasing with increasing temperature.

Nabaro [18] showed that at low creep rates, e.g. strain rates 10^{-11}/sec, essentially, the transfer of matter occurs by the migration of vacancies rather than by slide of dislocations. Since the sources and sinks of vacancies are GB's, the vacancies may diffuse through the bulk of the grain or along the GB's. Movement occurs orthogonally to the slip plane [11,12]. Ying et al. [12] showed with increasing the σ_t, the failure mode would be change from intregranular dominated to transgranular dominated.

5 DISCUSSION

As it was discussed previously, it can be concluded that TMF in solder joints would cause both fatigue and creep simultaneously. Both have been affected and controlled by several parameters, and each parameter has positive and negative influences on each mechanism at different levels. For example, Table 1 gives a summary of grain size effect on both mechanisms. Fine grains provide high σ_y, and Brinell hardness HB, which increase the fatigue life [15,20]. However, larger area of GB's (fine grains) would weaken the creep resistance [2-5]. Moreover, the fatigue and creep strength both have higher values when the loading direction makes normal angles with the atomic planes, due to speeding up the deformations with τ on inclined angles. In addition to that, it is obvious that creating σ_t will accelerate crack fatigue initiation, and da/dN, while σ_c acts to increase the fatigue life [20].

According to such qualitative interpretations and predictions, the table shows that the creep mechanism would be a main failure in solder joints at low stresses, either at high or low temperatures. However, when the applied stress is high, the main mechanism is fatigue. The reason behind this conclusion can be referred to; at high homologous temperature and with continuous lower stress, solder joints deformed under the influence of creep controlled by dislocation climb during early tensile stage. In the other words, dislocation climb creep is important for high stresses, and relatively low temperatures. Moreover, it also can be explained as a fact that, generally, raising the temperature encourages creep mechanism, and increases the fatigue life within increasing the K values of a material [1-5,18,20].

It is obvious, this study has considered only a few parameters that affect solder joint failures, i.e. some other parameters are not considered such as chemical composition, strain rate, frequency, etc. Moreover, such conclusions are not quantitative. However, whenever practical data is available, such kind of approaches, predictions, and interpretations would be useful and would be able to characterisation and modelling the solder properties with applied variables, and would be possible to considering the effect of any parameter and recognising which mechanism has a main influence on failure in solder joints [6-8]. For instance, although this study has not taken in consideration, in details, the effect of internal stresses (residual stresses), however, whenever such values are available, certain reasonable approaches and predictions can be obtained which helps diagnose the main mechanism that would affect on the solder joint failure, e.g. when the fatigue is a main mechanism, creation σ_c would be useful to retarding crack initiation. Accordingly, after doing required calculations, the designer or the manufacturer would be able to focus on the main mechanism for increasing the reliability and life time.

Fine Grains (large GB's Area)	Creep life	Temp.	High	Dec.	Main Mechanism in TMF	High σ High T	Creep
			Low	Inc.			
		Grain direct.	45°	Dec.			
			90°	Inc.		Low σ High T	Creep
		Applied stress σ	High	Dec.			
			Low	Inc.			
	Fatigue life	Internal stress	Tens.	Dec.		High σ Low T	Fatigue
			Comp.	Inc.			
		Grain direct.	45°	Dec.			
			90°	Inc.		Low σ Low T	Creep
		Strength	HB	Inc.			
			σ_Y	Inc.			

Table 1: Characterising he effect of grain size on TMF.

In the other side, it is worth to mention that such type of calculations, i.e. converting such qualitative interpretations to quantitative values, is possible with using statistical methods, i.e. probability values, and recognising which parameters are significant. Such predictions can be used as a starting point to describe the positive or negative effects of each parameter, and giving them logical influences to be used as a database for predictions, using computer software, such as expert systems, neural networks., etc, which gives immediate advices and answers for designers.

6 CONCLUSIONS

1- There is a possibility of treating the parameters that affect on creep and fatigue mechanisms of solder joints separately and combined.

2- A few parameters have dual and opposite effects on both mechanisms. With considering the interactions between those parameters, it is possible to recognise, qualitatively, the main mechanism that cause solders joint failure.

3- Converting such opposite parameters to quantitative values, within mathematical and programming models, might help the designers to reduce the size, reliability, and cost.

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