Validation of Virtual Life Management®
for
Electronic Solder Materials

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Abstract: Electronic failures can result in immediate system shutdown with no advanced fault or warning signal. As a device is operated thermal and/or mechanical loads are induced across the package. These loads are translated from the global package level to the localized interconnect level. VEXTEC's patented material-based simulation software accounts for real world interconnect variability and predicts probably of failure as a function of device operating time. Interconnect material families have been described within the approach according to their microstructural properties. Although this tool was originally developed and validated based on large structures (i.e., turbine engine components), it is now being used to predict small scale damage accumulation within electronic packages. This paper discusses the various aspects of the simulation approach. By linking manufacturing process variability with microstructural variability, this product can successfully provide a more complete and robust design analysis than typically afforded through traditional testing.

Keywords: interconnect; modeling; package; prognosis; solder; thermal fatigue.

Introduction:

Products are composites of many component elements all combined together to create a final overall product. The reliability of the final system is a function of the reliability of all of the parts, including interconnections between the parts. Disregarding operator error—e.g., a bolt didn't get tightened, or dials on the production line were grossly miss set—products fail because of a material failure in a component or interconnect. Materials fail because repetitive stress applied over time causes internal micro-structures (e.g. grain domains) to move or distort sufficiently to nucleate a discontinuity which leads to the propagation of a small crack, leading to a larger one, and finally to outright material failure.

Electronics, are reliant on the integrity of interconnects or solder bonds. The reliability of interconnects is a concern because it is widely expressed that fracture failures in solder joints accounts for up to 70% of failures in electronic components. Conventionally the reliability of electronic devices is assessed using empirically-based models. Design of experiments is a commonly used tool in which the experimental conditions are systematically varied and a mathematical relationship is "fit" to the data that represents the influence of the conditions to the time or cycles to failure. However, one problem is the fact that there is so much variation in the time or cycles to failure that device life can only be conveyed in the form of a statistical average, such as mean time to failure (MTTF) or the mean time between failure (MTBF). Although these statistical averages provide a general sense about average overall failure, they are a hold over from a time when computer processing power was expensive. They only provide information on a single point value and with no insight about real world probabilistic variation, true failure mechanisms or the impact those mechanisms have on how a specific design will react to actual field conditions.

Solder Fatigue:

The most commonly used fatigue models are based on Coffin-Manson plastic strain equations. Due to the low melting temperatures, most electronic devices operate at temperatures above solder creep thresholds. Since Coffin-Manson models do not explicitly address creep strains, specific solder models have been developed to incorporate creep [1]. All of the fatigue models in use today assume large scale similitude i.e., the structure (weld footprint or wire diameter) is large compared to the crack, the crack is large compared to the crack tip plastic zone and the crack tip plastic zone is large compared to the microstructure. These assumptions are fundamentally incorrect for today's small scale devices.

Energy-based solder fatigue models have been developed to account for the large crack size compared to the weld geometry [2, 3] and address the importance of the size of the material microstructure compared to the size of the damage. Emitter bond wires are usually 300 to 500 microns in diameter and the metalization layer to which they are bonded have a thickness of 3 to 5 microns. With polycrystalline grain sizes as large as 150 microns, microstructural similitude cannot be assumed for crack initiation and growth.

None of the previously described fatigue models account for the large scatter in the solder weld properties. The nature of the packaged components and variability within the assembly process creates large variations in the solder welds for even the strictest manufacturing tolerances. The very small size of the welds causes variation of the weld footprint from weld to weld. In addition, the microstructural development of the weld is greatly controlled by rate of cooling from the reflow stage. Conventionally used electronic device reliability prediction, largely empirically derived, do not account for this real world variability. Thus, variation in the geometry and material properties of the weld must be considered in order to prognosticate reliability accurately.

VPS-MICRO^{TM} is a probabilistic fatigue prediction capability that explicitly models fatigue damage (dislocations, slip band, small crack and long cracks) and the damage interaction with material microstructural features (crystallographic planes, phase boundaries, grain boundaries, etc.). VPS-MICRO^{TM} uses Monte Carlo techniques to simulate damage accumulation on a cycle by cycle basis. Monte Carlo reliability techniques are used so that model parameters such as loading, temperature and microstructure can simulate real world conditions by varying randomly with time.

Fatigue failure is a localized, material-driven process. An extensive amount of research has been conducted as to how and why cracks initiate and grow within solder connections. This knowledge was adopted within the developed local simulation modeling approach. High stresses are translated from global loadings to the local material. In particular these stresses exist at the interface between the copper lead and the solder. These localities are of compounded significance due to the existence of a complex microstructure of intermetallic layers between the copper and the solder. When molten Sn-Pb solder contacts the lead, intermetallic compounds (IMC) are formed between the solder and the lead. To model the complex stress state of the microstructure at the copper/solder interface, finite element models were created by VEXTEC for the copper/intermetallic/solder region (Figure 1). Because the thickness of the intermetallic layers change with time, a series of finite element models must be incorporated within the modeling approach.

Simulation of Solder Material Fatigue:

This section documents VEXTEC's success in predicting lead solder fatigue response at high temperature based on model development with room temperature data. Thereafter, as indicated in Figure 2, it was assumed that the same failure mechanisms driving lead solder response were active in lead-free response and fatigue predictions were made for lead-free solder material.

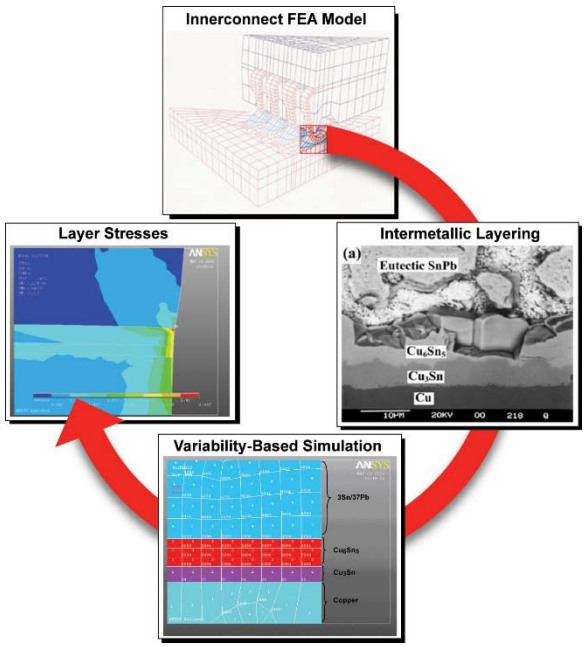

Figure 2: Global stress translated to local microstructure through simulation of intermetallic layers in solder.

Prior to this effort, VPS-MICRO™ had only been used to simulate fatigue for aerospace materials and structures (i.e., nickel, titanium, steel, etc.) therefore the first step was to develop an input library for solder alloys. Needed were the appropriate input parameters for simulation of damage mechanisms at the microstructural scale. This simulation procedure must account for variations in material parameters like grain size, grain orientation, crack growth coefficients and inherent strength of the grains. Since 63Sn-37Pb eutectic solder alloy has been extensively studied by the electronics industry, this material seemed to be a logical starting point. Material performance data on this alloy are widely available at various temperatures and frequencies. Table 1 presents a listing of the model input parameters used for 63 Sn-37Pb simulations along with the references from which these data came. As indicated in the table, values for some parameters could not be found in the literature available to VEXTEC. Therefore, engineering judgment was used to estimate these parameter values and fatigue was predicted for a strain range of 2%. These predictions were compared to experimental data in [4]. Thereafter these few parameters were further adjusted until the model successfully replicated these limited experimental data at 25°C. Upon achieving satisfactory results at 2% strain range, the complete 25°C S-N (strain range – number of cycles to failure) curve was predicted for lower strain ranges (Figure 3). Unfortunately VEXTEC had no experimental data available to compare with these predictions. As shown in Figure 3, VPS-

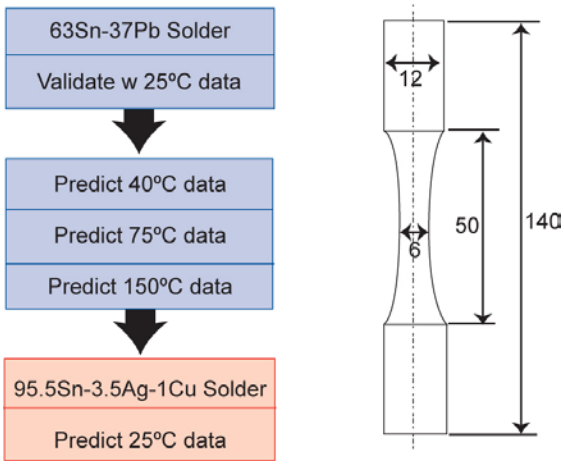

Figure 1: Process used for predicting lead and lead-free solder fatigue.

Table 1: Input parameters required for simulation of lead solder fatigue.

Parameter	Reference
Bulk shear modulus	Siewert *et al.* (5)
Poisson's ratio	Siewert *et al.* (15)
Grain size and phases	Liu *et. al.* (6)
Small crack growth coefficient	None
Long crack growth coefficients	Zhao *et al.* (7)
Frictional strength (grain level yield strength)	Siewert *et al.* (5)
Grain boundary SIF	Zhao *et al.* (7)
Orientation factor	None
Specific fracture energy	None

MICRO™ predicts the expected scatter in fatigue life. The art and science of modern day fatigue analysis can now account for the real world microstructural variability that exists in solder materials.

This model, developed based on 25°C data, was then used to make higher temperature predictions for the same Sn-Pb solder alloy. This was accomplished by first studying the effect of temperature on the material properties of the Sn-Pb solder and making appropriate modifications to model input parameters. Figure 4 shows the comparison of the predictions at 25°C and 150°C. Through the open literature, VEXTEC was able to access a single 150C fatigue test data point for this material. As shown in the figure, this data point falls within the expected scatter at approximately 0.7% strain range. This suggests that the model can successfully simulate solder temperature effects. As expected, the 150°C fatigue lives are lower than those at 25C. It is interesting to note that the model predicts that the effect of temperature is more pronounced at lower strain ranges than at higher ones.

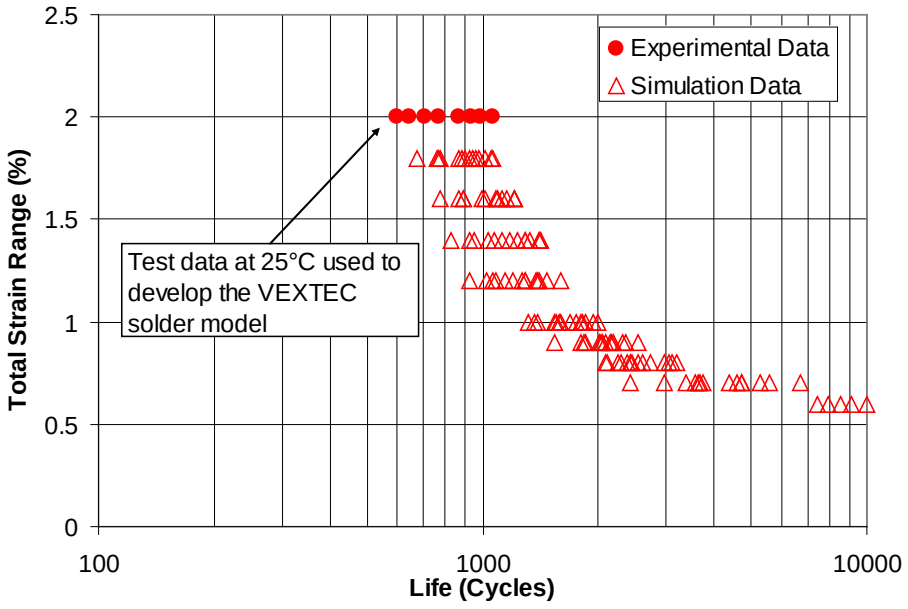

Figure 3: Fatigue simulation for 63Sn37Pb at 25°C, 1Hz.

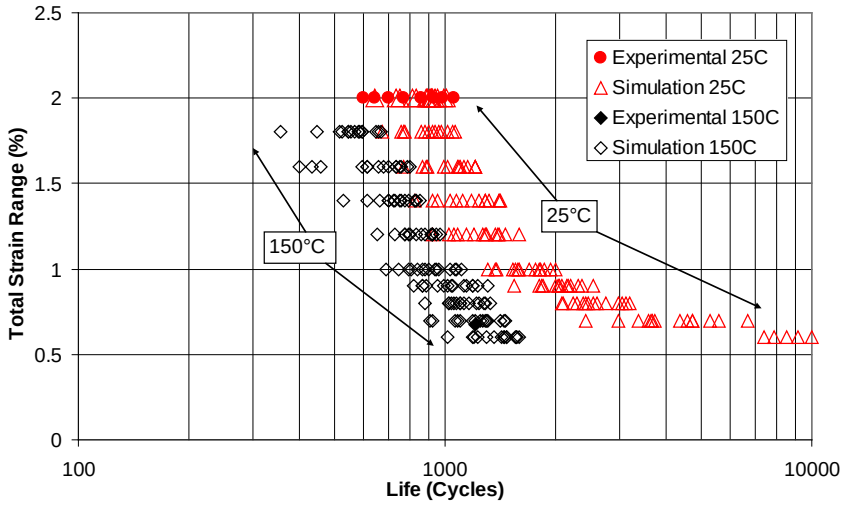

Figure 4: Comparison of 63Sn37Pb fatigue predictions at 25°C, 1Hz and 150°C, 1 Hz.

Simulations were also made at 40°C and 75°C since VEXTEC was able to obtain a single test data point for each of these temperatures. Again the actual fatigue test point was within the predicted scatter for the appropriate strain range; therefore, VPS-MICRO™ appears to be successfully predicting temperature effects on solder fatigue life. Figure 5 presents a comparison of the mean predicted life with experimental data at the appropriate strain range.

Prediction of Lead-Free Solder:

As stated previously and shown in Figure 2, it was assumed that the same failure mechanisms driving lead solder response were active in lead-free response. Therefore the VPS- MICRO™ inputs were only modified to account for collected information about microstructural properties (i.e., grain size) and bulk material properties. Thereafter VPS-MICRO™ was used to make fatigue predictions for lead-free solder material. Since the national electronics manufacturing

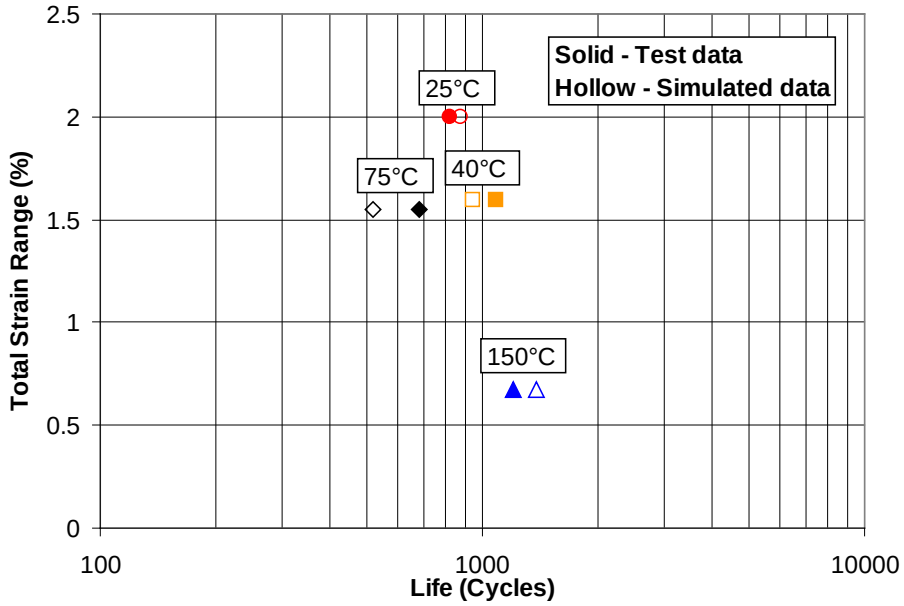

Figure 5: Comparison of mean simulation values with test data at various temperatures.

initiative (NEMI) has suggested that 95.5Ag-3.5Sn-1.0Cu solder has promising characteristics for wide spread electronic industry use, that material was selected for VEXTEC evaluation.

Table 2: Input parameters required for simulation of lead-free solder fatigue.

Parameter	Reference
Bulk shear modulus	Modified based on data in Siewert *et al.* (5)
Poisson's ratio	Modified based on data in Siewert *et al.* (5)
Grain size and phases	Modified based on data in Amagia *et al.* (8)
Small crack growth coefficient	Unchanged
Long crack growth coefficients	Changed based on data in Zhao *et al.* (7)
Yield strength of the grain	Unchanged
Grain boundary SIF	Modified based on Zhao *et al.* (1)
Orientation factor	Assumed
Specific fracture energy	Unchanged

The properties the input parameters used in VPS-MICRO™ are listed in Table 2. Some parameters did not change from those used for lead material predictions. This was purposeful or just due to lack of reliable information about what they should be.

VPS-MICRO™ was used to make 25°C, 1Hz fatigue predictions and compared with limited experimental data available in [4]. As shown in Figure 6 the predictions accurately capture the two experimental data points presented in the referenced paper. Along with the lead-free predictions, the earlier presented lead solder predictions at 25°C are shown in Figure 6. The simulations show a very interesting feature, the lead and lead-free fatigue lives cross over. This suggests that lead solder actually performs better than lead-free solder at lower strain ranges. One possible reason for this could be the strain hardening effect that occurs when the lead-free solder

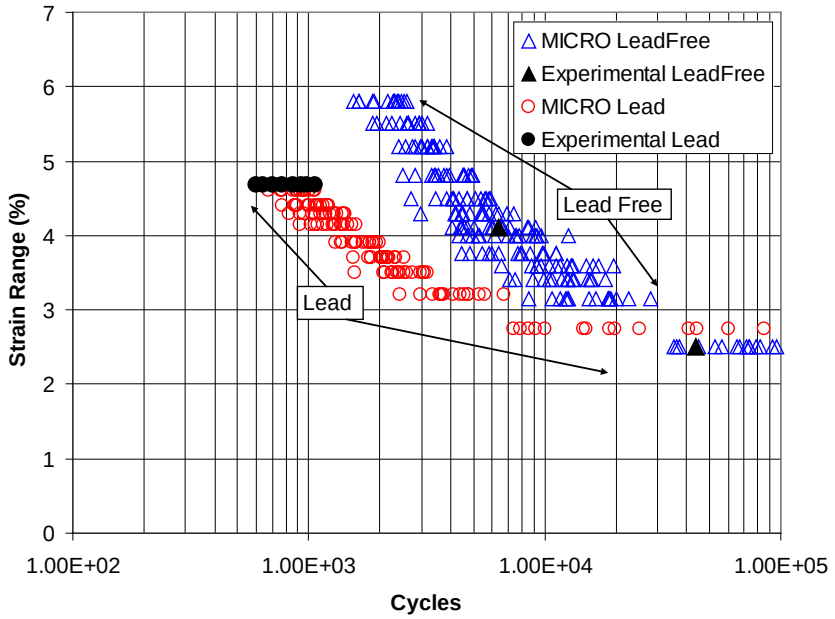

Figure 6: Comparison of lead and lead-free solder predictions at 25C, 1Hz.

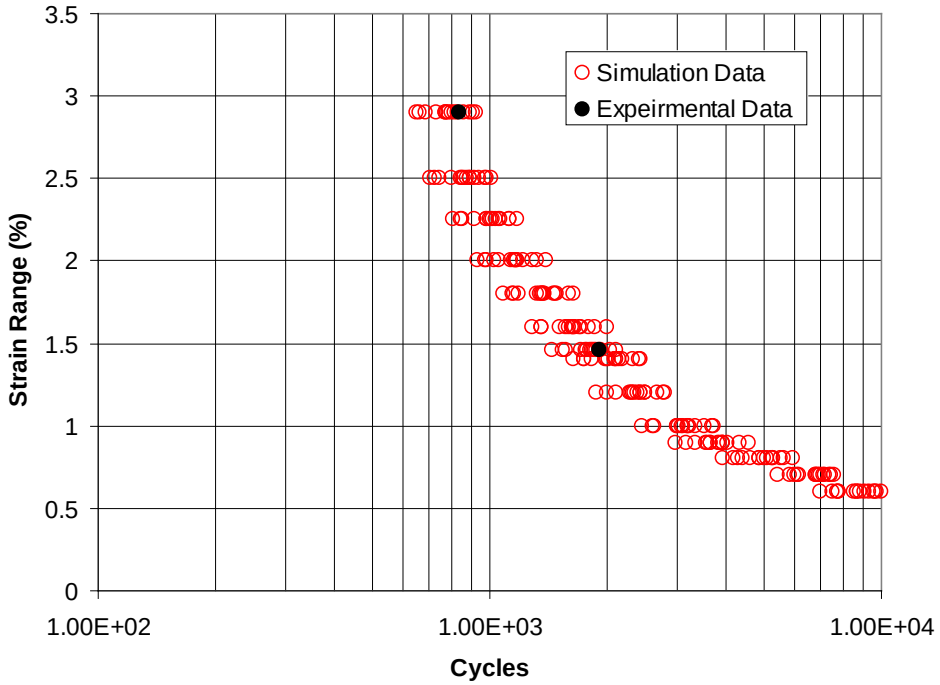

Figure 7: Lead-free solder predictions at 125°C, 0.001Hz.

material is at room temperature. This strain hardening nature was observed in one hysteresis loop assumed to be the cycle at half life. Further data on cyclic hardening is needed to verify the strain hardening phenomenon. Further it must be noted that the results shown here are for a laboratory material specimen and not for an actual solder joint geometry. For an actual solder joint, other issues such as thermal residual stresses, intermetallics play a role influencing fatigue life.

The final step in this process was to verify that VPS-MICRO™ could successful predict the temperature effects on lead-free solder fatigue. Fatigue predictions at 125°C, 0.001 Hz lead-free solder are presented in Figure 7. Within VPS-MICRO™, only the material properties were modified to account for the temperature and frequency change effects. As shown, these predictions compare well with single experimental result obtained from [4].

Summary:

Although VPS-MICRO™ was originally developed to predict fatigue response for aerospace structural materials, this paper clearly demonstrates the successes achieved in predicting both lead and lead-free solder material performance. This paper presents the progressive steps in developing the MICRO material model for 63Sn37Pb lead solder and then predicting temperature effects. It was also shown that, considering the same failure mechanisms as for lead, the simulation approach can successfully predict 95.5Sn 3.5Ag 1.0Cu lead-free solder response and temperature effects. The assumption that the damage mechanisms remain the same irrespective of the solder alloy composition appears to be valid based on comparisons between VPS-MICRO™ simulation results and appropriate test data. Assuming this is true, the electronics industry will be capable of simulating years worth of lead-free material testing within a fraction of the time required for conventional prototype build-test-analyze. The next step in this process will be the application of VPS-MICRO™ in predicting fatigue life and scatter for actual microelectronic packages.

References:

1. S. Knecht., L. Fox. (1991) “Integrated matrix creep: application to accelerated testing and lifetime predictions, “Solder joint reliability theory and applications,” Van Nostrand Reinhold, New York.
2. J. Liang, N. Gollhart, P. S. Lee, S. Heinrich, S. Schroeder, (1997) “An integrated fatigue life prediction methodology for optimum design and reliability assessment of solder inter-connectors,” Advances in Electronic Packaging, Vol. 2.
3. J. W. Morris, H. L. Reynolds, (1997) “The influence of Microstructure on the mechanics of eutectic solders,” Advances in Electronic Packaging, Vol. 2.
4. J.H.L Pang, B.S. Xiong, T.H. Low, ‘Low cycle fatigue models for lead-free solders,’ Thin Solid Films, Vol. 462, pp. 408, 2004
5. A. Schubert, R. Dude, E. Auerswald, A. Gollhardt, B. Michel,. M.H. Reichl, ‘Fatigue life models for Sn-Ag-Cu and Sn-Pb solder joints evaluated by experiments and simulations,’ Electronic Components and Technology Conference, pp. 603, 2003
6. X. W. Liu, W. J. Plumbridge, ‘Thermomechanical fatigue of Sn-37 wt.% Pb model solder joints,’ Materials science and engineering, Vol. A362, pp. 309, 2003
7. B.A. Zahn, ‘Solder joint fatigue life model methodology for 63Sn37Pb and 95.5Sn4Ag0.5Cu materials,’ Electronic Components and Technology Conference, pp. 83, 2003
8. X.Q. Shi, J.H.L. Panh, W. Zhou, Z.P. Wang, ‘Low cycle fatigue analysis of temperature and frequency effects in eutectic solder alloy’, International journal of fatigue, Vol. 22, pp. 217, 2000
9. X. Q. Shi, J.H.L. Panh, W. Zhou, Z.P. Wang, ‘A modified energy based low cycle fatigue model for eutectic solder alloy,’ Scripta Materialia, Vol. 41, pp. 289, 1999
10. J. Zhao, Y. Mutoh, Y. Miyashita, L. Wang, ‘Fatigue crack growth behavior of Sn-Pb and Sn-based lead-free solders,’ Engineering Fracture Mechanics, Vol. 70, pp. 2187, 2003
11. G. Lefranc, T. Licht, G. Mitic, ‘Properties of solders and their fatigue in power modules,’ Microelectronics Reliability, Vol. 42, pp. 1641, 2002
12. M. Amagai, M. Watanabe, M. Omiya, K. Kishimoto, T. Shibuya, ‘Mechanical characterization of Sn-Ag based lead free solders,’ Microelectronics Reliability, Vol. 42, pp. 951, 2002
13. I. Shohji, T. Yoshida, T. Takahashi, S. Hioki, ‘Tensile properties of Sn-Ag based lead-free solders and strain rate sensitivity,’ Materials science and engineering Vol. A3666, pp. 50, 2004
14. K. Kishimoto, T. Shibuya, ‘Mechanical characterization of Sn-Ag based lead-free solders,’ Microelectronics reliability, Vol. 42, pp. 951, 2002
15. H. Tang, C. Basaran, ‘Experimental characterization of material degradation of solder joint under fatigue loading,’ Inter Society Conference on Thermal Phenomena, pp. 896, 2002
16. K. Stinson-Bagby, ‘Microstructural evolution in thermally cycled large area lead and lead-free solder joints,’ Master’s thesis, Virginia Polytechnic Institute and State University, 2002
17. T. Siewert, S. Liu, R.D. Smith, C.J. Madeni, ‘Properties of lead-free solders, release 4.0,’ National institute of standards and technology and Colorado school of Mines, 2002