Physics based Prognostics of Solder Joints in Avionics

Avisekh Banerjee[1], Ashok K Koul[1], Amar Kumar[2], Nishith Goel[3]

[1] *Life Prediction Technologies Inc., 23-1010 Polytek Street, Ottawa, Ontario, K1J 9J1, Canada*
banerjeea@lifepredictiontech.com
koula@lifepredictiontech.com

[2] *Tecsis Corporation, 200-210 Colonnade Road, Ottawa, ON, K2E 7L5, Canada*
amar@tecsis.ca
[3] *Cistel Technology, 40-30 Concourse Road, Nepean, ON, K2E 7V7, Canada*
ngoel@cistel.com

ABSTRACT

Applicability of a physics based prognostics approach for solder joints using microstructural damage models is investigated. A modified deformation mechanism map for the solder alloys is introduced where grain boundary sliding (GBS) plays a dominant role during creep deformation. The high homologous temperature of solder as well as the combined thermal-vibration cycling experienced during typical operating missions necessitates the use of a combined creep-fatigue failure approach. In this work, a PCB consisting of a heat generating chip with Ball-Grid Array (BGA) solder joints is considered for avionics application. A prognostics based Life Cycle Management approach was used to perform the mission analysis, FEA, thermal-mechanical stress analysis and damage accumulation analysis. The remaining useful life (RUL) is predicted for different rupture strains. The uniqueness of this approach lies in the use of microstructure based damage models and consideration of both material and mission variability to predict the RUL under actual usage. The life critical nodes were observed near the junction of the solder joints with the substrate due to high disparities in their coefficients of thermal expansion. In addition, the probabilistic analysis was also performed by randomly varying the grain size and fitting a two-parameter Weibull distribution to the failure data. The model calibration and the results show some practical trends that need to be verified through future experimentation. The simulation results demonstrate the viability of using a physics based approach for the prognosis of solder joint failures in avionics.

1. INTRODUCTION

Life prediction analysis of solder joints is a popular, but challenging topic due to high occurrence of failures in the field. The mechanical fault progression leads to electrical failure of solder joints causing about 70% of overall failures in avionics. The failures of the fundamental avionic components like transistors and their interconnections are mostly caused by operating thermal, mechanical and electrical overstresses (Saha, Celaya, Wysocki & Goebel, 2005). Previous studies have considered empirical (Kalgren, Baybutt, Ginart, Minnella, Roemer & Dabney, 2007) or only simplified physics based thermal fatigue (Nasser, Tryon, and Dey, 2005) models for the prognostics of electronic components. However approaches involving top-down multi-component analysis techniques (Kalgren, et al., 2007) combined with empirical models require the availability of significant amount of data along with considerable deviation from the norm to predict the presence of a fault. This makes the early detection or prediction of damage or faults very difficult. Moreover, the relative scaling of electronic components and detectable crack sizes limits the use of traditional empirical damage models from a life prediction or prognostics perspectives. In contrast, only considering thermal fatigue induced transgranular fractures of solder joints (Nasser et al., 2005) may not provide an accurate fault prediction because creep damage may also contribute to the overall damage accumulation process.

The Pb-Sn solder joints in electronic packages function as electrical interconnections, as well as mechanical bonds. The solder joints often consist of materials possessing different thermal expansion coefficients and this imposes cyclic strains under thermal loading fluctuations. Thermal fluctuations can occur due to external temperature variation or internal heat dissipation. These temperature fluctuations can be large in electronic components in avionics. Even small temperature fluctuations can lead to significant cyclic strain accumulation, depending upon the size of the joint and the difference in the thermal expansion of the joined materials. One of the most important requirements of the new solder materials is the reliability of the solder joints against thermal cycling, flexural bending, and impact loading. An in-depth understanding of the micro-mechanistic processes leading to the solder joint failures under conditions of thermal-mechanical fatigue and creep has been achieved through great deal of research (Dasgupta, Sharma & Upadhyayula, 2001; Joo, Yu & Shin, 2003; Kovacevic, Drofenik & Kolar, 2010; Shi, Wang, Yang & Pang, 2003).

Due to the high homologous operating temperatures, deformation of solder joints is always governed by a combination of creep and TMF processes. Solder joints are exposed to time dependent high temperature deformation mechanisms associated with creep and residual stress relaxation and the joints are also susceptible to low cycle fatigue (LCF) damage accumulation. Creep is the most common and important micromechanical deformation mechanism operative in the solder joints that eventually leads to failure. Microstructural features also influence the material properties and plastic deformation kinetics greatly. For Sn-Pb solders, the phase boundaries are known to be the preferred crack initiation sites. The cracks then propagate preferably along tin–lead or tin–tin grain boundaries (Joo et al., 2003). Continuous TMF loading will also induce creep deformation effects. Since room temperature for eutectic Sn-Pb alloys is around 0.65 T_m (T_m is the melting temperature in K), phase changes due to diffusion can also be expected to play a role at higher temperatures leading to accelerated damage accumulation.

Fatigue damage due to vibration loading leads to cyclic plasticity while that due to temperature cycling causes cyclic creep. Plastic deformation of the solder refer to instantaneous time scale and primarily occurs due to slip; while creep due to time dependent and diffusion-assisted mechanisms over long time, namely grain boundary sliding, dislocation glide/climb and mass transport through the grain boundary/matrix. Furthermore, there are interactions between vibration and temperature damage accumulation rates due to factors like material properties changes; microstructural coarsening and interaction between vibration stress and the TMF stress.

The lead-free SAC (Sn-Ag-Copper) is the alternative alloy as Pb is harmful to the environment and human beings. The alloys melt around 250 °C, depending on their composition. Different variations of the SAC alloy, with Ag content from 3.0% to 4.0% are all acceptable compositions. Creep rupture in SAC occurs by the nucleation of cavities and their subsequent growth by continued creep damage accumulation. The 1.5Cu SAC shows the poorest creep ductility because of the brittle cracking of the intermetallic Cu_6Sn_5, which provided easy nucleation and crack propagation sites for creep cavities (Joo et al., 2003).

These observations suggest that a number of deformation and failure mechanisms contribute to solder alloy system deformation and fracture depending mainly on applied stress and temperature. Some of these mechanisms include plasticity, dislocation creep and grain boundary deformation accommodated by different processes. To assess the current health and RUL of solder joints, it is important to employ the appropriate constitutive models for deformation and fracture. Combining the constitutive models for various regimes is useful for determining the creep strain rates and the remaining useful life (RUL) for solder joints (Kovacevic et al., 2010; Shi et al., 2003).

Gu and Pecht, (2010) provide several examples of implementing prognostics and health assessment for electronics products in the industry and defense applications. The paper also discusses how the traditional handbook-based reliability prediction methods for electronic products like MIL-HDBK-217 are being replaced by PHM. Approaches like physics-of failure, data-driven and their combination has been discussed in detail.

Hence a reliable physics based prognostics system including both mission as well as microstructural variabilities possess a good potential for facilitating the accurate prediction of the RUL of the PCB. This would enable a user to gauge the health of an existing PCB and optimally plan maintenance schedules as well as help in designing PCBs to withstand the loads for the intended application.

2. PHYSICS-BASED PROGNOSTICS FOR AVIONICS

In this paper, a prognostics-based Life Cycle Management framework is proposed to predict the RUL of avionic components. The combined effect of creep and thermal fatigue loads is considered on the damage evolution leading to intergranular as well as transgranular deformation of solder joints. The major causes of failure of solder joints are TMF cycling arising from the operational changes as well as creep due to the presence of a high operating temperature in terms of the homologous temperature of the eutectic solder. The soldering process also imparts intrinsic residual stresses that arise due to the difference in the thermal properties of the solder/intermetallic/substrate. The stress relaxation caused by the grain/phase boundary sliding leads to creep deformation of the solder joint also leads to crack nucleation during service. At the same time, the variation in the operating loads leads to TMF damage accumulation. The intergranular and transgranular deformation based combined creep-fatigue approach to damage accumulation would thus provide a more accurate simulation of the actual failure of the solder joints and it would also lead to more accurate predictions.

2.1 Deformation Mechanisms

A deformation mechanism map for the Pb-Sn eutectic solder is shown in Figure 1. The deformation mechanism map is a stress-temperature diagram presenting the dependency of normalized stress τ/G (G is the shear modulus) on homologous temperature T/T_m. Elastic region exists only at the very slow strain rate ($<10^{-10}$), while plastic region occurs over yield strength level. The dislocation controlled creep regime consists of three subzones, namely high stress creep regime, low temperature (LT) dislocation glide creep regime, and high temperature (HT) dislocation climb creep regime. Below this regions of creep, the two diffusion controlled regimes exists, namely grain boundary (GB) regime and matrix diffusion regime.

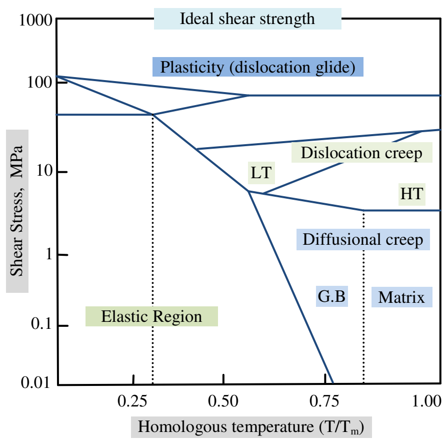


Figure 1: Line diagram for deformation mechanism map of Sn-Pb eutectic solder alloy highlighting the essential features

In parallel with Ashby's deformation mechanism map, Mohammed and Langdon (1974) considered an alternative to this map where grain boundary sliding (GBS) instead of diffusion creep predominates. Other attempts to accommodate GBS field in Ashby type maps have also been presented by Koul, Immarigeon and Wallace (1994). In 2002, Wardsworth, Ruano and Sherby (2002) conducted a detailed analysis of all the data on the diffusional creep of engineering alloys and concluded that GBS dominated the deformation which had commonly been confused with diffusional creep. Based on the mechanistic modeling work of Wu and Koul (1993 and 1995), Wu, Yandt and Zhang (2009), presented an alternate map for engineering alloys.

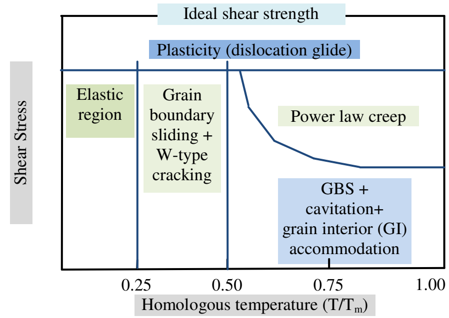


Figure 2: Modified deformation mechanism map with grain boundary sliding

These changes have been incorporated in the form of modifications to the deformation mechanism map presented in Figure 1, while considering the creep behavior of eutectic solder in this study, Figure 2**.**

PROBLEM FORMULATION

In this work, the problem of prognosis of electronic circuit boards in avionics has been considered and the RUL of solder joints is predicted. A detailed 30 hour long mission suitable for a typical transportation aircraft has been designed and used to determine the operating conditions during the mission. The problem is treated as combined creep and TMF damage accumulation process and analysis based on the microstructural properties of eutectic solder in a Ball-Grid Array (BGA) subject to the mission experienced by the transport aircraft is carried out. The circuit board is assumed to be located in the forward avionics bay of a transport aircraft consisting of a chip (BT substrate) with 8 solder joints mounted on an FR4 board as shown in Figure 3. The dimensions of the different components are also shown in the figure. The substrate has been assumed to have internal heat generation capacity with convection cooling allowing the heat distribution over the entire circuit. The operating conditions like ambient temperature, acceleration change along with the specific mission also need to be considered in physics based prognostics approach. Hence it is proposed that the mission as well as the microstructural variability have to be simultaneously considered for accurate prognosis.

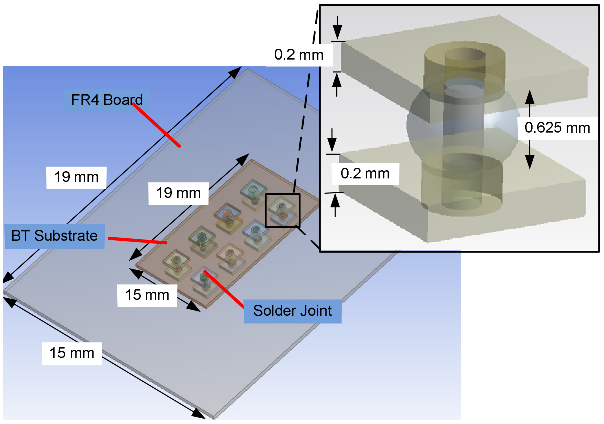


Figure 3: Typical geometry of a PCB for Avionics

4. PROGNOSTICS BASED LCM METHODLOGY

A bottom-up prognostics based Life Cycle Management (LCM) approach (Koul, Tiku, Bhanot & Junkin, 2007) has been adopted. This involves the systematic consideration of the requisite inputs like material and geometry of the components and the usage. The temperature, stress and strain is calculated to determine the microstructural damage accumulation based nodal life enabling the determination of the RUL as well as the fracture critical location/node. The framework of the prognostic approach is shown in Figure 4 with each module described in details as below:

- **Input Data**

  Component geometry: The three dimensional model of the component is created to generate the mesh for subsequent FEA.

  In-service operating data: This is required to utilize the actual usage of the component rather than designed usage for more accurate prognosis. Typical operating data collected are RPM, Altitude since it governs the ambient conditions, from where other dependent parameters are calculated to determine the relevant parameters of the mission profile.

  Material Data: Microstructural data like grain size, boundary precipitate size, activation energy, etc are requisite for the damage analysis. Simultaneously temperature dependent and independent physical data like elastic modulus, poison ratio, conductivity, etc are also required for materials used for every component.
- **Pre-Processing**

  Mission profile analysis: Once the mission has been obtained from the in-service operating data, a fuzzy logic based mission profile analyzer is used to determine the creep and fatigue loads on the components, their duration or frequency and their sequence.

  Thermal and Structural Loading: Based on the in-service operating condition and the mission profile analysis, thermal and mechanical loads are determined along with the requisite boundary conditions to closely replicate the effect of service exposure.

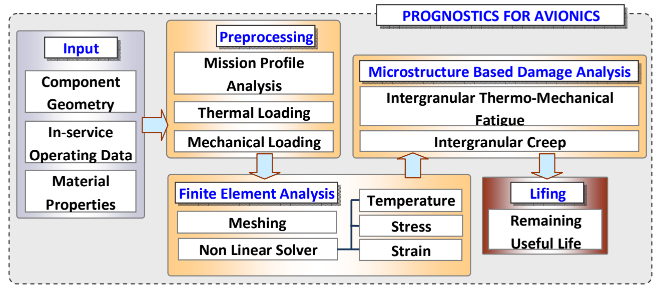


Figure 4: Framework of prognosis based LCM for solder joints in avionics

  Finite Element Analysis: Well structured and mapped mesh is generated from the component geometry to conduct the thermal and structural analysis under the pre-determined loading and boundary conditions to calculate the nodal temperature, stress and strain.
- **Microstructure based Damage Analysis**

  Microstructure based damage models under inter-granular, transgranular and combined creep (Wu and Koul, 1995) and thermo-mechanical fatigue (Neu and Sehitoglu, 1989) has been implemented. These models take into account the microstructure, physical properties and their variation with temperature, operating condition and calibration of empirical coefficients with experimental data.
- **Life Prediction Analysis**

  Based on the nodal temperature, stress and strain obtained from FEA, microstructural damage models are applied at each node to determine the accumulated damage as a result of the creep and fatigue loads. Robinson and Miner's damage summation rule is applied to determine the total damage accumulated during each mission and RUL is calculated for each node. This also allows the determination of the primary, secondary and tertiary facture critical locations.

5. SIMULATION SETUP

5.1 Geometry and Meshing

Geometry of the PCB consisting of 8 BGA solder joints, one BT substrate and one FR4 board was created as shown in Figure 3. Structured mapped mesh was generated and symmetry was used as shown in Figure 5 to reduce the computational cost. The two solder joints are numbered 1 and 2 for ease of referencing in the subsequent text. A total of 17663 quadrilateral 3D mesh elements were used for a quarter symmetric model.

5.2 Material Data Collection

Three different types of data were collected, as below:

- *Microstructural data*: Grain size, boundary precipitate size, interlamenar distance, activation energy, diffusion coefficient, etc.
- *Physical properties*: Temperature dependent and independent physical properties like Young's Modulus, Poison's Ratio, Density, CTE, etc.
- *Calibration data*: Creep (strain vs. time) and fatigue test (strain vs. number of cycles) data for solder material (Sn63Pb37).

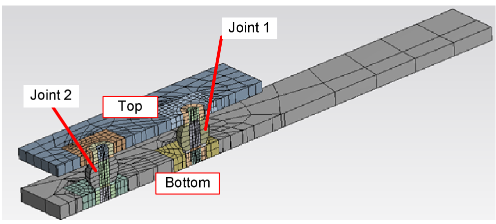
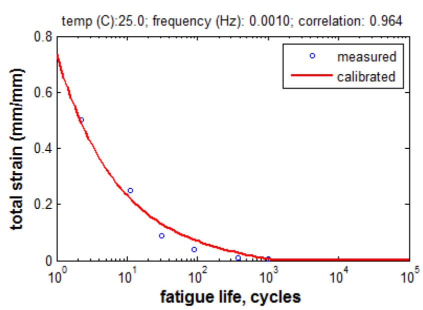


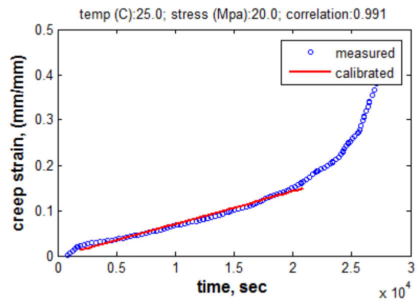
Figure 5**:** Sectional view of mesh for quarter symmetric circuit board

5.3 TMF and Creep Modeling

The microstructural based damage models for intergranular creep and TMF were calibrated for the eutectic solder alloy. For the creep model, experimentally measured creep life (strain vs. time) test data (Wong, Lau & Fenger, 2004) was utilized to calibrate the measured strain rate due to intergranular deformation caused by grain boundary sliding. For the fatigue model, experimentally obtained fatigue life data (strain vs. number of cycles) was used to calibrate the empirical material constants (Shi, Wang, Yang, & Pang, 2003). The microstructural data for eutectic solder was also obtained from existing literature and applied to both models. The calibrated TMF and creep models with experimental data are shown in Figure 6.



(a) TMF



(b) Creep

Figure 6**:** Calibration of intergranular damage models

5.4 Mission Profile Analysis

Mission profile closely representing that of a transport aircraft is required. For this purpose a detailed mission profile for typical transport aircraft was generated for a total flight duration of 30 hours with the cruise altitude being around 9,000 meter. Details of the mission were included by incorporating the change in the rpm and altitude at different stages of the mission, as shown in Figure 7. The other dependent parameters like ambient temperature, ambient pressure, acceleration were calculated. An initial temperature of 25°C was assumed at the ground level. Ambient temperature along the mission was calculated from the altitude in the mission which affects all the avionic components. The ambient temperature was added to the temperature profile generated by the chip's internal heat generation and convective cooling to determine the resultant temperature at every time step of the mission. Moreover the vibratory acceleration amplitude exerted on all the components was also calculated as a function of rpm (Tang & Basaran, 2003; Smith, 2004) along the mission. Based on the temperature and acceleration profile, a fuzzy logic based mission profile analyzer was implemented to determine the creep and fatigue loads on the solder joint. The calibrated damage models were invoked at every time step based on the type of loading.

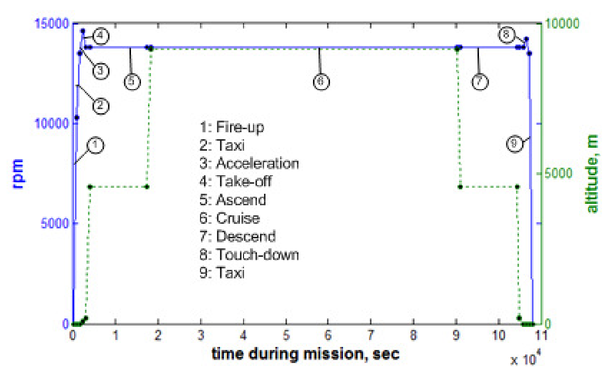


Figure 7**:** Designed mission profile

5.5 Boundary Conditions

The simplified substrate was assumed to have an internal heat generation of 0.5W/mm^3 during its operation period which was assumed to be constant throughout the mission. A closed case convection for the front avionics bay region was assumed to have a coefficient of 20W/m^2°C. The PCB was fixed at the four corners to represent attachment with the aircraft structural frame with screws. The RPM dependent acceleration was applied on all the components which would allow the four corners with least displacement where as the centre of the circuit board would have the maximum deflection.

5.6 Finite Element Analysis

The FEA analysis was performed with ANSYS Workbench with a coupled steady-state thermal and structural analysis. At first the temperature loads were applied on to the components and the thermal results were carried forward for subsequent structural analysis.

6. LIFING ANALYSIS

6.1 Remaining Useful Life

The temperature, stress and strain calculated from FEA based on the mission profile and other operating conditions were applied to the microstructural creep and TMF models. The result of the FEA namely temperature, stress and strain at each node of solder were calculated at each time-step with different fatigue damage models to determine damage accumulated at each node. Robinson and Miner's rule was used to sum the damage (D) for creep and fatigue loads at each load (i=1 to n) as below:

$$D = \sum_{i=1}^{n} \frac{t_i}{t_f} + \sum_{i=1}^{n} \frac{N_i}{N_f} \tag{1}$$

where t_i is the creep duration and N_i is the number of fatigue cycles for the i-th load, t_f and N_f are the failure creep duration and fatigue cycle. The remaining useful life (RUL) was calculated from the D and the total mission duration time (t_M) as below,

$$RUL = \frac{t_M \times (1 - D)}{D} \tag{2}$$

6.2 Probabilistic Analysis

Once the deterministic life critical nodes were identified based on the nodal temperature, stress and strain over the solder joints, a probabilistic analysis was conducted. In this analysis, the microstructural variability in terms of the grain size variation was considered. The grain size was selected as a major parameter since it plays an important role in the damage accumulation processes arising from combined creep and fatigue mechanisms. For the purpose of studying the variation in the RUL for different grain sizes, a normal distribution of the grain size was considered. The mean size was the deterministic grain size and the standard deviation was assumed based on variations observed due to different reflow process parameters. Upon randomizing the grain size, probabilistic lifing calculation was carried out under steady-state operating conditions with Monte Carlo Simulation. A two parameter Weibull distribution of the probabilistic remaining useful life was also estimated for the most critical node.

7. RESULTS AND DISCUSSION

7.1 Finite Element Analysis

At first the temperature profile was calculated based on the ambient temperature, heat generated by the chip and convective cooling at each time step of the mission. A typical temperature profile is shown in Figure 8 (a). The temperature was highest over the chip which generates constant heat during the operation. The temperature was lowest at the board furthest away from the heat source, approximately resembling the ambient temperature condition. The thermal loads generated when combined with the mechanical load of vibratory acceleration resulted in maximum deflection at the centre of the board and chip being furthest away from the fixed support as shown in Figure 8 (b). The equivalent stresses and strains were found to be highest near the bottom surface of the solder Joint 1 which is due to the combination of higher temperature variation between the solder and the board as well as lower deformation due to closeness to the fixed support. The typical FEA results in terms of stress and strain distributions are shown in Figure 8 (c) and (d).

7.2 RUL Calculation

The spatial distribution of RUL for different rupture strains is shown in Figure 9. The figure shows that the region close to the bottom interfacing surface of Joint 1 has the lowest life owing to the higher stress and strain concentration and it is most likely to fail at this location. This can be explained on the basis of the presence of higher temperature gradient and lower deformation since its closeness to the fixed support leads to higher stresses.

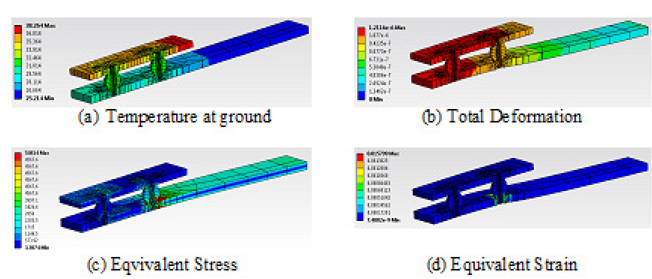


Figure 8: Typical FEA result over the PCB segment

Again more accurate RUL calculation should involve the consideration of the intermetallic layer between the solder and the substrate whose material characterization was beyond the scope of this work. The primary life critical node is at node number 4805 with a RUL of 7,041 hrs. Considering that the intermetallic layer would be highly brittle which makes the selection of a low rupture strain ($\varepsilon_{rupture}$) of 0.05% to calculate RUL as the most appropriate engineering solution to this problem. This suggests that the intermetallic layer has to be embrittled to a point where creep failure is dramatically influenced by its volume fraction.

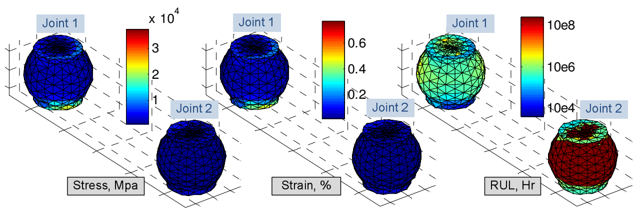


Figure 9**:** Spatial distribution of stress, strain and RUL over two solders joints

A range of rupture strains were used to recalculate RUL at the life critical node of 4805 along with the damage contribution of TMF and creep and tabulated in Table 1. The table shows that the contribution of the TMF is the largest towards damage accumulation in the solder joints during the normal operation of the aircraft. In-flight cyclic fluctuations will be expected to dominate the contribution to the damage accumulation process.

7.3 Probabilistic Analysis

After determining that the primary fracture critical node is at 4805 node number with 0.05% rupture strain with the RUL

Table 1: RUL and contribution at fracture critical node of 4805

$\varepsilon_{rupture}$ (%)	RUL (Hrs)	% Contribution to Damage	
		TMF	Creep
0.001	4,611	61.83	38.17
0.005	6,652	89.03	10.97
0.010	7,041	94.21	5.79
0.050	7,386	98.80	1.20
0.100	7,431	99.41	0.59
0.500	7,468	99.90	0.10
1.000	7,473	99.97	0.03

being 7,386 hrs, a Monte Carlo simulation was conducted with 5,000 normally distributed random samples of microstructural grain size with mean grain size of 2µm and standard deviation of 0.40µm. The Weibull distribution plot of remaining useful life calculated for the randomly distributed grain size at the primary fracture critical node is shown in Figure 10. Since the β>1 it suggests that the usage based failure of the solder with the Mean Time to Failure (MTTF) to be approximately around 8,000 hours service life of the solder joints. Contribution to damage from creep becomes prominent only at very low and may be unrealistic rupture strains. However, for a detailed consideration, creep damage accumulation during ground idle and time between flights should also be included.

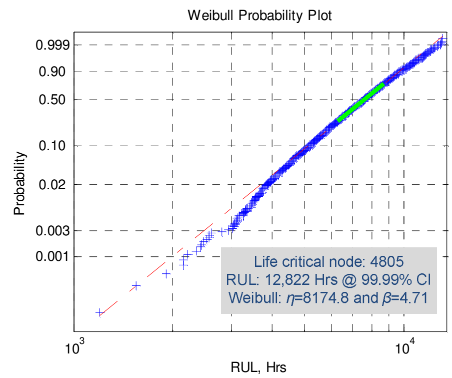


Figure 10**:** Two parameter Weibull distribution of RUL at life critical node of 4805

8. CONCLUSIONS AND FUTURE WORK

A prognostics based Life Cycle Management approach has been proposed to implement a physics-based prognostic system for eutectic solder joint in avionics. Realistic mission profiles and eutectic solder properties have been incorporated to calculate RUL of the solder joints in a typical PCB under combined thermal and vibratory loading conditions. Microstructure based damage models for creep and fatigue have been calibrated with the properties data for the eutectic solder. Finite Element Analysis and RUL results indicate that the contact surface between the solder and the board accumulated the highest damage thus making it the most likely failure prone zone. It is also observed that the contribution of TMF damage accumulation is dominant during the aircraft operation. The deterministic and probabilistic lifing analysis reiterates the applicability of the prognosis based LCM of solder joints. Further work towards developing more comprehensive prognosis of avionics would include the following:

- Improving the TMF and Creep models by using frequency and cavitation terms
- Extension of the prognosis of other avionics components
- Experimental validation with standardized accelerated life testing in laboratory environment

REFERENCES

Dasgupta, A., Sharma, P., & Upadhyayula K. (2001). Micro-Mechanics of fatigue damage in Pb-Sn solder due to vibration and thermal cycling, *International Journal* *of damage mechanics,* vol. 1, pp. 101-132.

Gu, J., & Pecht M. (2010). Prognostics and Health Assessment Implementation for Electronics Products, Journal of the IEST, vol. 53, no. 1, pp. 44-58.

Joo, D. K., Jin Y., & Shin S. W. (2003), Creep rupture of lead-free Sn-3.5Ag-Cu solders, *Journal of electronic materials*, vol. 32, No. 6, pp 541-547.

Kalgren, P. W., Baybutt, M., Ginart, A., Minnella, C, Roemer, C. M. J., & Dabney T. (2007). Application of prognostic health management in digital electronic systems, *IEEE Aerospace Conference*, pp. 1-9.

Koul, A. K., Bhanot, S., Tiku, A., & Junkin B. (2007). Importance of Physics-Based Prognosis for Improving Turbine Reliability: RRA 501KB Gas Turbine Blade Case Study, *ASME 2007 Power Conference*, San Antonio, Texas, USA.

Koul, A. K., Immarigeon, J. P. & Wallace, W. (1994). Microstructural Control in Ni-Base Superalloys. In *Advances in High Temperature Structural Materials and Protective Coatings* (95-125). National Research Council of Canada, Ottawa.

Kovacevic, I. F., Drofenik, U., & Kolar J. W. (2010). New physical model for lifetime estimation of power modules, *International Power Electronics Conference*, ETH, Zurich, pp. 2106-2114.

Mohamed, F. A. & Langdon, T. G. (1974). Deformation Mechanism Maps Based on Grain Size. *Metallurgical Transactions*, 5, 2339-2345.

Nasser, L., Tryon, R. & Dey A. (2005). Material simulation-based electronic device prognosis, *IEEE Aerospace Conference*, pp. 3579-3584.

Neu, R., & Sehitoglu, H. (1989), Thermomechanical fatigue, oxidation, and Creep: Part II. Life prediction, *Metallurgical and Materials Transactions A*, vol. 20, pp. 1769-1783.

Saha, B., Celaya, J. R., Wysocki, P. F., & Goebel K. F. (2009). Towards prognostics for electronics components, *IEEE Aerospace Conference*, Big Sky, MT, pp. 1-7.

Shi, X. Q., Wang, Z. P., Yang, Q. J., & Pang H. L. J. (2003). Creep behavior and deformation mechanism map of Sn-Pb eutectic solder alloy, *Journal of Engineering Materials and Technology,* ASME, vol. 125, pp. 81 - 87.

Smith, S. D. (2004). Cockpit seat and pilot helmet vibration during flight operations on aircraft carriers, *Aviation, Space, and Environmental Medicine*, vol. 75, no. 3, pp.247-254.

Tang, H., & Basaran C. (2003). A damage mechanics-based fatigue life prediction model for solder joints, *Transactions of the ASME*, *Journal of electronic packaging*, vol. 125, pp.120-125.

Wong, T. E., Lau, C. Y., & Fenger H. S. (2004). CBGA solder joint thermal fatigue life estimation by a simple method, *Soldering & Surface Mount Technology*, 16/2, 41–45.

Wadsworth, J., Ruano, O. & Sherby, O. (2002). Denuded zones, diffusional creep, and grain boundary sliding. *Metallurgical and Materials Transactions A, Chemistry and Materials Science*, 33(2), 219-229.

Wu, X. J., & Koul A. K. (1995). Grain boundary sliding in the presence of grain boundary precipitates during transient creep, *Metallurgical and Materials Transactions A*, vol. 26, pp. 905-914.

Wu, X. J., Yandt, S. & Zhang, Z. (2009). A Framework of Integrated Creep-Fatigue Modelling. *Proceedings of the ASME Turbo Expo 2009* (GT2009-59087), June 8-12, Orlando, Florida, USA.

Dr. Avisekh.Banerjee is Senior Mechanical Engineer at Life Prediction Technologies Inc. (LPTi), Ottawa, ON. He is working on the development of a prognostic based LCM system for avionics. His area of research and interests is diagnostics, prognostics and data trending for failure detection and development of PHM framework.

Dr. Ashok Koul is the President of Life Prediction Technologies Inc. (LPTi), Ottawa, ON and also acts as an overall technical advisor. He has 25 years experience in the field of materials engineering and life prediction with extensive experience in managing and supervising research and development activities in gas turbine structures, materials and life cycle management strategies. Over the years he has made key contributions in identifying and applying existing as well as emerging technologies in the field of gas turbine engineering.

Dr. Amar Kumar has more than 25 years of research and consulting experience in the fields of structural materials characterization, development and applications. At present Dr. Kumar is working as senior research scientist in the development projects of diagnostics, prognostics and health management. Prior to joining the current assignment in 2006, he was employed with Indian Institute of Technology at Delhi, India as a teaching faculty after obtaining his PhD degree from the same Institution. Dr. Kumar has published more than 200 research papers in refereed journals, conference proceedings, and technical reports.

Dr. Nishith Goel is a Founder and President of Cistel Technology Inc. He served as a Technical Advisor and Member of the Scientific Staff of Nortel Networks from 1984 to 1999. Dr. Goel is the co-founder of iPine Networks, Norleaf Networks and CHIL Semiconductor. He has been a Director of Enablence Technologies Inc. and is the Chair of the Queensway-Carleton Hospital Foundation board. Dr. Goel holds an MA in Science, Electrical Engineering and a PhD in Systems Engineering from the University of Waterloo.