EFFECT OF AGING ON SAC305 SOLDER JOINTS RELIABILITY IN ACCELERATED FATIGUE SHEAR TEST

Raed Al Athamneh[1], Mohammed Abueed[1], Dania Bani Hani[1], Sa'd Hamasha[1]
[1]Department of Industrial and Systems Engineering
Auburn University, 3301 Shelby Center, Auburn, AL 36849
rqa0001@auburn.edu

ABSTRACT

Lead-free solder joints are used to provide electrical and mechanical connections between the printed circuit board and electronic components. The robustness of every single solder joint is vital for the reliability because any failure in a solder joint may ruin the overall function of an electronic device. Mechanical and thermal cyclic stresses are the most common factors that lead to failures in solder joints. Aging is another factor that changes the mechanical properties. The most critical applications of electronic assemblies are found in harsh environments where solder joints are under cyclic stress at elevated temperatures for a long time. This study aims to assess the reliability of the most common solder material under different cyclic stress levels and aging times at an elevated temperature. Individual SAC305 (96.5 % tin, 3% silver, and 0.5% copper) solder joints are cycled in an accelerated shear fatigue experiment using Instron 5948 Micromechanical Tester. The stress amplitude levels are 16 MPa, 20 MPa, and 24 MPa and the aging times are 0, 2 hrs, 10 hrs 100 hrs and 1000 hrs where the aging temperature is held constant at 100°C. The number of the experimental combinations tested is fifteen. Seven solder joints for each combination were used. Two-parameter Weibull distribution was developed for each combination to assess the reliability. The plastic strain and the inelastic work per cycle were calculated from the hysteresis loops. The results showed that increasing the stress amplitude leads to less reliability and larger inelastic work per cycle and plastic strain. The results also showed that increasing the aging time leads to less reliability and larger inelastic work per cycle and plastic strain. Power equations were used to fit the correlations between the characteristic fatigue life, stress amplitude, aging time, inelastic work per cycle, and plastic strain. A general model was developed as well to predict the reliability based on the stress amplitude level and aging time.

Key words: SAC305, solder joint, aging, reliability, fatigue, Harsh Environment

INTRODUCTION

One of the most common factors that affect the reliability of the electronic devices is the fatigue failure of the solder joints. Solder joints provide the electrical connections between the printed circuit board (PCB) and the electronic components, and it provides mechanical support of the electronic components. Several studies explicated the changes in microstructure due to isothermal aging and thermal cycling and its effect on the reliability and mechanical behavior. The most common material that was used for fabricating the solder joint is eutectic or near eutectic tin/lead (Sn/Pb) solder where it has robust reliability and outstanding solderability. Several concerns were present because of the health issues that are associated with the leaded solder material and its effect on the environment. In the last three decades, the electronic industries, and the research centers in the US and worldwide worked in developing reliable lead-free solder alloys being considered as green products. [1-3]

The Sn-Ag-Cu (SAC) series are the most popular alloys that are utilized in fabricating the solder joints for lead-free applications because of its low cost, manufacturability, reliability, and availability. [4] Several case studies investigated the reliability and the mechanical behaviors for lead-free solder alloys, specifically, for SAC solder alloys. Those studies assessed the probability of failure for different solder materials under different working conditions of aging and compared their performance with leaded solder alloys (SnPb). Tusi et al. studied the effect of aging at room temperature on the shear strength of SnPb. and a degradation model was developed. The study found that there is no significant effect of 12 hours aging on the shear strength for SnPb solder balls. On the other hand, the shear strength drops 10% after aging 3 days at room temperature. [5] Ma et al. demonstrated the effect of 6 months aging at room temperature on the mechanical properties for SAC solder alloys. The large reductions in the stiffness, strain, ultimate strength and yield stress to failure were found to be approximately 40%. [6] Coyle et al explored the effect of room temperature annealing or age softening on the shear strength and the hardness of the SnPb and SAC alloys. The significant decreases in the shear strength and the hardness were determined for SnPb and SAC alloys. The microstructure for both alloys was studied to identify the failure mode and to correlate the evolutions in the microstructure with the shear strength and hardness. [7]

Lee et al. studied the effect of aging on the long term reliability for BGAs with SAC 305 solder alloy. The thermal cycling test was implemented by cycling the temperature between 0ºC and 100ºC where the aging temperatures were 100ºC and 150ºC. The outcomes from the test showed that 44% reduction on lifetime happened when the aged solders at150ºC were used. However, aging at 100ºC presented a lower effect on the lifetime with a similar pattern. [8] Smetana et al. inspected the effect of isothermal aging on a variety of electronic components by using thermal cycling fatigue test. The temperatures that were utilized in the thermal cycling test are 0ºC and 100ºC. The results proved that it is not always the aging or preconditioning process that has a negative impact on the lifetime of the electronic components. Where in some cases, the aging process enhances the reliability of certain components especially when the cycling temperatures range between 20ºC and 80ºC. [9]

Zhang et al. studied the effect of isothermal aging on the mechanical properties of the lead-free solder alloys and leaded Sn-37Pb solder alloy. Creep was one of the mechanical properties that was impacted significantly by the isothermal aging of the lead-free solder alloys. In contrast, Sn-37Pb solder had a lower rate of creep than lead-free solder alloys. This is because the evolutions on the microstructure in lead-free solder alloys were higher than those happened on Sn-37Pb solder. The main reason of shifting in the mechanical behavior was blocking dislocation movement that leads to a reduction in strength for lead-free solders which usually happen in high temperatures and harsh environments. [10]

Another study by Li et al. explored the shear strengths for Sn-0.7Cu, Sn-3.8Ag-0.7Cu, Sn-3.5Ag and Sn-Pb eutectics solder bumps. These eutectic solder bumps were aged for 51 days at room temperature. The 5-8% reduction in the shear strength for lead-free solder bumps was reported. [11] Zhang et al. utilized the thermal cycling test to determine the reliability of the Sn-1.0Ag-0.5Cu (SAC105), Sn-3.0Ag-0.5Cu (SAC3 05) and Sn-37Pb solder ball interconnects under different aging temperatures. The fine -pitch ball grid arrays (BGAs) with three different surface finishes (ImAg, ImSn, SnPb) were used as a testing part and the solder joint aged at 25ºC, 55ºC, 85ºC and 125ºC for 12 months. The results for aged solder alloy were compared with the results for non-aged solder alloy. The degradation model for each experiment combination was constructed. The study showed that the service life of the package was reduced after aging and the amount of reduction in the service time for the package had a negative relationship with the aging temperature. The worst case happened at 125ºC with 58% reduction in the service time compared to non-aging package. The Sn-37Pb solder ball presented better results in terms of service time of the package compared to the SAC alloys. [12]

In their paper, Zhang et al. implemented an accelerated shear fatigue test to predict the reliability of the solder joint and measure the accumulated work that was consumed to cause failure and the evolutions in the plastic deformation. Hamasha et al. performed fatigue shear experiments on SAC305 and SAC105 solder joint to study its reliability at different stresses and to determine the accumulated work and the plastic strain. The power equations predicted the reliability under different conditions and were used to relate the stresses, accumulated work, characteristic life and plastic strain together. The experimental results showed that SAC305 has more fatigue resistance than SAC105, where there is no significant differences on the effect of strain rate in both alloys. [13]

Lall et al. explored the impact of the strain rate on the mechanical behavior for SAC105 and SAC305 solder alloys extensively. The effect of aging on the mechanical behavior at different aging temperatures and times were investigated. The temperatures that were utilized in the aging process are 25ºC, 50ºC, 75ºC and 100ºC and the durations at each aging temperature are 1 day, 30 days and 60 days. The non-linear Ramberg-Osgood model was used as a fitting model for aged and unaged specimens by using two fitting methods which are statistical regression fit and closed-form model approach. The elastic modulus, the ultimate tensile strength, and stress-strain curve have been determined in the strain rate range 1-100sec^{-1}. The experimental results showed that the impact of aging duration at elevated temperature on the ultimate tensile strength is higher than its effect on the elastic modulus. [14] Han et al. have explored the creep behavior and correlated it with the indentation size for SAC357 lead-free solder. [15]

Venkatadri et al investigated the influence of aging on lead-free solder joints. The study was done by utilizing the micro hardness test to implement single idents on the joints. [16] Hasnine et al. determined the influence of different aging conditions for SAC305 solder joints on the stress-strain and creep behavior. The elastic modulus, yield stress, and hardness were characterized as a function of aging. The creep output was determined as a function of stress level by exploiting Nano indentation techniques. The aging effect on SAC305 solder joint was correlated with those effects on bulk solder specimens that are tested previously. The results presented that the degradations of the modulus and hardness of both single grain SAC305 joints and miniature bulk specimens are similar. On the other hand, the degradations of creep response in the solder joints were significantly lower than the degradations of bulk specimens. In the same study, the correlation between crystal orientations of aged specimens and the mechanical properties was found, and the prediction model of the tensile creep strain rate at low-stress levels by employing the Nano indentation test data that were determined at high compressive stress levels. [17]

The coarsening of overall microstructure and the size of the precipitate particles was examined in room temperature aging by Chuang et al. where the shifting on the tensile properties for the Sn-9Zn and Sn-9Zn-0.5Al eutectic solder alloys was explored under 30 to 180 days of aging under 30 ºC. The results have demonstrated that the grain size of tin-rich was increased and recrystallized when the solder alloys exposed to 35 days of aging at room temperature. [18] The differences in the distribution of precipitate in the bulk sample and solder joint were recognized by Anderson et al. and the effect of the intermetallic layer (IMC) which is formed from the metallurgical reaction between PCB and the solder paste was studied. The results show that a negative relationship was found between the thickness of IMC and the fatigue life. [19]

Another study by Zhang et al. studied the impact of the percentage of silver in the SAC alloys composition on the mechanical behavior under aging conditions. The percentages that were studied are 1%, 2%, 3% and 4% silver with alloys containing 0.5% copper and the aging temperatures were 25ºC, 50ºC, 75ºC, 100ºC, and 125ºC. The solder joints were aged for various durations (0-6 months). Several doped SAC solder alloys were tested to examine the effect of using dopants on the drop reliability and to test the ability of dopants to enhance the thermal cycling reliability under aging condition. Analogous tests were applied for 63Sn-37Pb eutectic solder sample to compare it with lead-free solder alloys. The results show that aging at elevated temperature has a significant effect on the stress-strain and creep behavior of the solder joints and that the degradations for the strength and stiffness have a linear relationship with aging time. The creep rates for SAC solder alloys and tin-lead solder alloy have been increased exponentially where SAC solder alloys have higher creep rate at the beginning compared to the tin-lead alloy. The results also showed an increase in the sensitivity of mechanical behavior with a low percentage of silver in SAC solder alloys when exposed to the aging process. Those changes in the mechanical behavior after aging are due to the evolution in the microstructure. In the first phase of aging when the particles are small and fine precipitations, this leads to prevent the dislocation movements and the grain boundaries sliding which enhances the strength of the material and creep resistance. In contrast, in the second phase, the particle size is increased which reduce their ability to prevent the grain boundary sliding and dislocation movements. Thus the resistance to creep deformations and the strength for SAC solder alloys were reduced. [20]

Based on the previous literature and study findings, the reliability, the mechanical properties and the microstructure for the lead-free solder alloys can be changed over time when exposed to isothermal aging process. One of the main reasons of studying the effect of isothermal aging is that the electronic products usually spent months or even years to be delivered from its manufacturing factory to the final customer which is known as the aging effect on the hand-held consumer product. [12]

MATERIALS AND METHOD

Test Sample Preparation:

The test boards are used by constructing printed circuit boards (PCBs) from FR-4 glass epoxy substrates with a full array of SAC305 (96.5Sn-3Ag-0.5Cu) solder joints. The pitch distance between the solder joints is 3mm, and the solder joint diameter is 30mil. The surface finish used in the test boards is Organic Solderability Preservative (OSP) where Solder Mask Defined (SMD) pads are utilized. The test set which contains nine solder joints as shown in Figure 1. The thickness of the PCB is 3mm, and the copper pad diameter is 22 mil. The reflow process was done in a nitrogen gas environment with preheat time (200 seconds) and temperature (235ºC) where the increasing temperature rate is 0.75 ºC. The detailed reflow profile is shown in Figure 2.

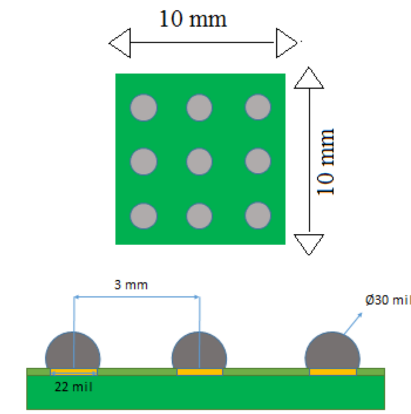


Figure 1: The Testing set

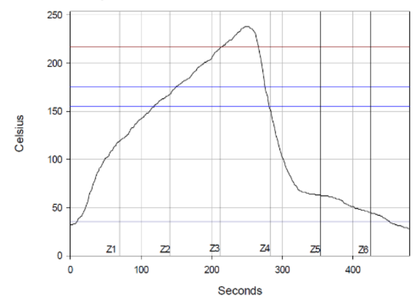


Figure 2: The Reflow profile

Testing Method:

Isothermal accelerated shear fatigue test is used to assess the reliability of the solder joints. Figure 3 shows the Instron 5948 MicroTester that is used to apply cyclic shear stress on individual solder joints. The tester has a 50N load cell and 20nm displacement resolution. The testing fixture was designed and manufactured to adapt the solder joint into the testing machine as shown in Figure 4.

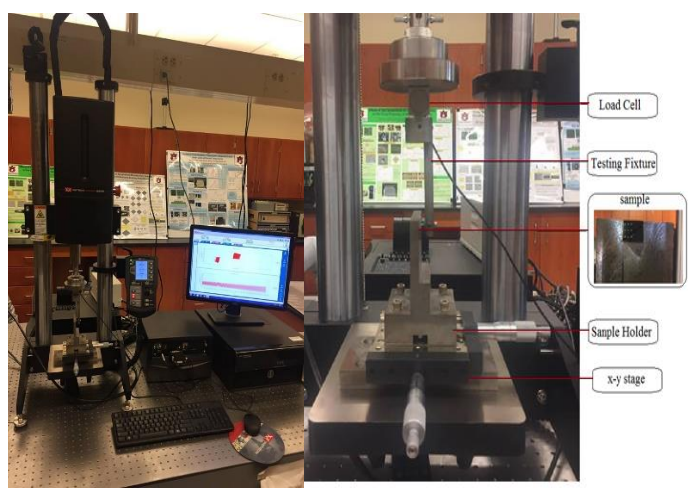


Figure 3: The Instron 5948 MicroTester

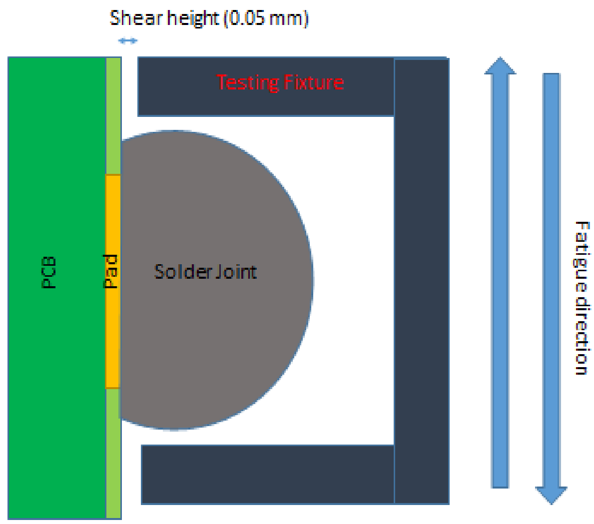


Figure 4: Schematic of the cylindrical testing fixture for individual solder joint

Test Materials and Conditions:
The solder alloy used in this experiment is SAC305. Four different aging times were applied to the testing samples under 100 ºC aging temperature and are compared with the original samples (without aging). The isothermal accelerated fatigue shear test was used to assess the reliability of the solder joint under different aging conditions. To construct a reliability model for predicting the life of the solder joint, the fatigue shear stress was applied under three different stress loads for each aging condition. According to these experimental conditions, the experimental structure has two factors that were studied for their effects on the reliability of the solder joint. The first factor is the aging time which has five levels (0 hrs, 2 hrs, 10 hrs, 100 hrs, and 1000 hrs) and the second factor is the stress amplitude with three levels (16 MPa, 20 MPa, and 24 MPa). The orthogonal array L_{15} is implemented with seven replicates for each experiment under which each experiment represents a different service condition. The orthogonal array for the experiment is shown in table 1.

The Methodology:
After performing the experiments, Two-parameter Weibull distribution was estimated for each test condition by using the maximum likelihood method. All of the Weibull distribution estimations were done by using MINITAB software. As a result, from the Two-parameter Weibull, the scale parameter which represents the number of cycles that has the 63.2% probability of failure and shape parameter which represents the slope in the Weibull plot were obtained. A power equation is utilized to predicate the fatigue life as a function of the stress amplitude as shown in equation 1. [21]

$N = a * P^{-c}$ ……………...………………………………(1)

Where N is the fatigue life of the solder joints under given aging condition and stress amplitude. The power value c is the material constant which represents the ductility of the material where the smaller value of c means a higher ductility and a is another material constant. P is the peak stress amplitude.

The fatigue life N versus stress amplitude P was plotted on a log-log scale to demonstrate the relationship, and it was fitted to the power equation. The relation between fatigue life N and aging time T and its fitted equation at different stress amplitudes is obtained. In order to study the earlier failures of SAC305 solder under different aging conditions and stress amplitude, 10% of the probability of surviving (B10) was calculated by using the Two-parameter Weibull distribution equation (2). The prediction equations are originated for the earlier failure of the solder joints at different aging times T and stress amplitudes P by plotting the B10 versus stress amplitude and B10 versus aging time. [22]

$R(t) = e^{-(\frac{t}{\theta})^{\beta}}$ …………………………...……………..…(2)

Where t is the fatigue life, $R(t)$ is the probability of surviving at time t (reliability), θ is the scale parameter and β is the shape parameter.

To calculate the inelastic work per cycle W and the plastic strain S, the steady state region in the solder joint life is defined. Then, the hysteresis loop at each cycle for each service condition is initiated. From the hysteresis loop, the inelastic work and plastic strain are determined, and the averages for the inelastic work and plastic strain were calculated at each service condition for the steady-state region. To find the effect of aging time on the average inelastic work per cycle, the log-log scale plot is generated to identify the relationship between the inelastic work per cycle and the aging time. The prediction equation for the inelastic work is obtained as a function of the aging time at different stress amplitudes. The relationship between the plastic strain and the aging time is demonstrated as well by using the log-log scale plot. The prediction equation of the plastic strain as a function of aging time is initiated at different stress amplitudes. As a result from this analysis, a set of fitted equations are obtained as a function of aging time and stress amplitude to predict the fatigue life, inelastic work, and plastic strain.

Table 1: The orthogonal array L_{15} for the experiments

Exp (i)	Aging time (hrs)	Stress amplitude (MPa)
1	0	16
2	0	20
3	0	24
4	2	16
5	2	20
6	2	24
7	10	16
8	10	20
9	10	24
10	100	16
11	100	20

12	100	24
13	1000	16
14	1000	20
15	1000	24

RESULTS AND DISCUSSION

Parametric Estimation for the Reliability:

Two-parameter Weibull distribution is constructed by utilizing the maximum likelihood as an estimation method for each condition. Figure 5 shows the Weibull distribution plots for SAC305 solder joints without any aging condition under three different stress amplitudes (16 MPa, 20 MPa and 24 MPa) with 95% confidence intervals for each plot. Figure 5 describes the drop in the reliability of the SAC305 solder joints when the applied stress is increased. Two-parameter Weibull distributions under different aging time and stress amplitude are shown in Figure 6 (a-c). The results represent the reduction in the fatigue life with increasing the aging time and this reduction is increased exponentially with increasing the aging time with a high reduction at the beginning then the amount of the reduction is decreased. The percentages of the reduction in the characteristic life of the solder joints under different aging times at each stress amplitude compared to the original samples of the solder joints (without aging) are illustrated in Figure 7. As a conclusion from Figure 7, the highest reduction in the characteristic life was 73% in the 1000 hrs aging and 20 MPa stress amplitude which is close to the reduction in 1000 hrs and 24 MPa of a 71% reduction. Moreover, the reduction in the characteristic life is increasing in an exponential behavior when increasing the aging time. The highest gaps of reduction were in 10 hr aging time for 16 MPa and 20 MPa stress amplitude and in 2 hrs for 24 MPa stress amplitude.

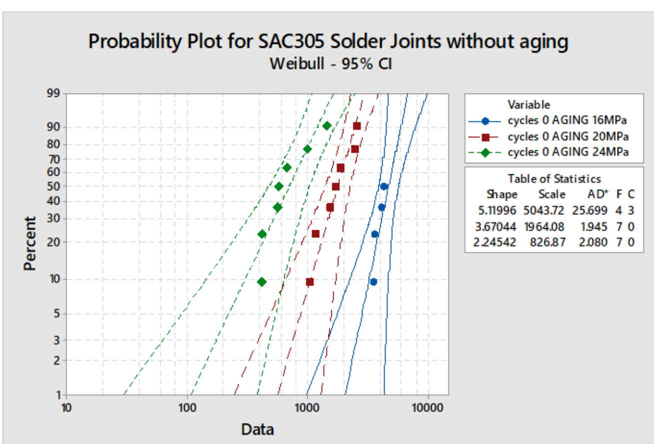
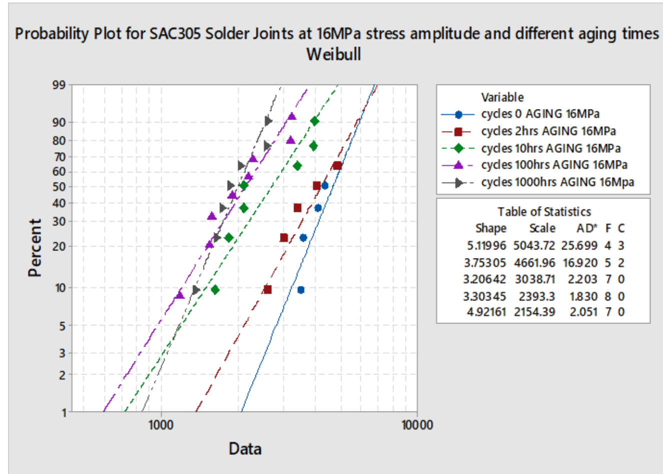
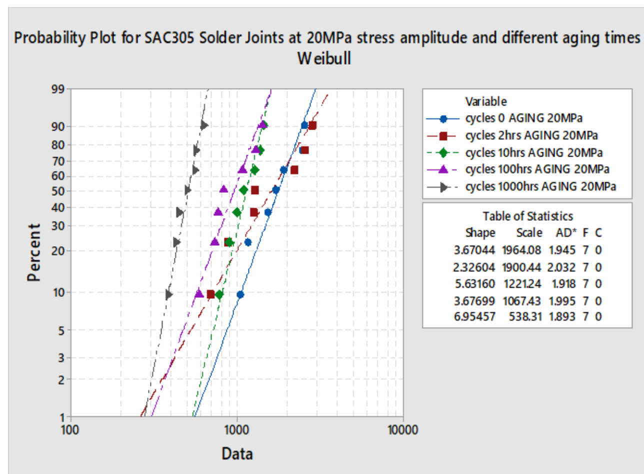


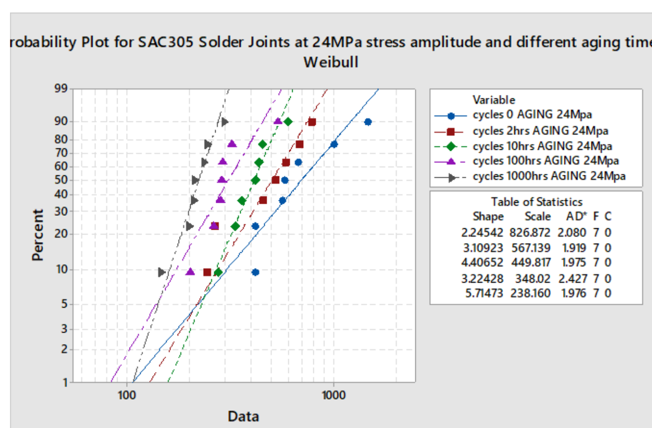
Figure 5: Two-parameter Weibull distributions for SAC305 without aging for different stress amplitudes



(a) Two-parameter Weibull distributions under 16 MPa stress amplitude and different aging times



(b) Two-parameter Weibull distributions under 20 MPa stress amplitude and different aging times



(c) Two-parameter Weibull distributions under 24 MPa stress amplitude and different aging times

Figure 6: Two-parameter Weibull distributions for SAC 305 solder joint distribution under different aging times and stress amplitudes

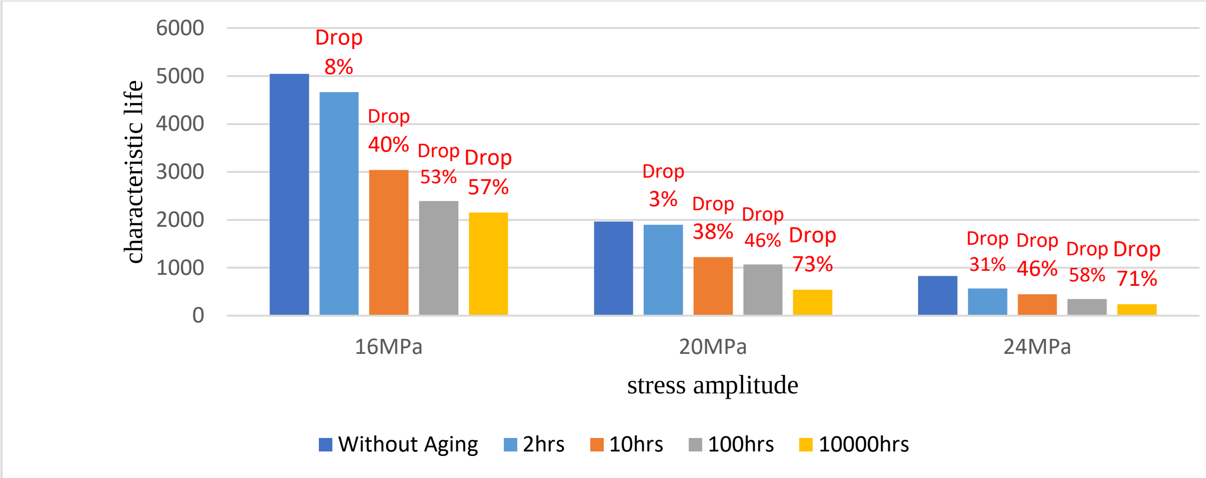


Figure 7: The characteristic life and the percentages of reduction in the characteristic life for lead-free SAC305 solder joints under different aging times

Prediction Model for the Fatigue Life:
Power equations are used to demonstrate the relationship between the stress amplitude and the characteristic life. Figure 8 shows the log-log scale plot and the fitted equation between the characteristic life and the stress amplitude for the SAC305 solder joints without aging. To demonstrate the effect of aging on the relationship between the characteristic life and the stress amplitude, the log-log scale plots and the fitted equations between the characteristic life and stress amplitude were developed for the SAC305 solder joints at different aging times as shown in Figure 9. To construct the prediction model at different aging times, the relationship between the characteristic life and the aging time is plotted in Figure 10. The power equation is exploited as a fitting equation to determine the characteristic life as a function of the aging time at different stress amplitudes. Where N is the characteristic life and P is the stress amplitude. To find the reliability model as shown in equation (2), the average shape parameter β at each aging time or stress amplitude should be found where the characteristic life θ can be obtained from the fitted power equations. In order to study the earlier failures of SAC305 solder joints at different aging times and stress amplitudes, the fatigue life with 10% probability of surviving (B10) is determined by using equation (2). Figure 11 identifies the relationship between B10 and the stress amplitudes and show its fitted equation for SAC305 solder joints without aging by implementing a log-log scale plot. The negative relationship between the stress amplitude and B10 is originated. The effect of aging time on the B10 under different stress amplitudes is determined in Figure 12. The decrease in the B10 when increasing the aging time is demonstrated.

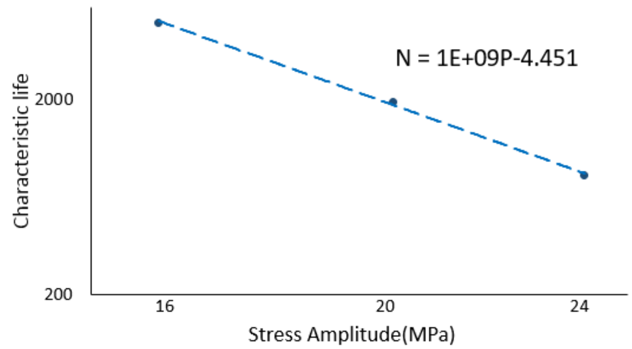


Figure 8: Characteristic life versus stress Amplitude for SAC305 solder joints without aging

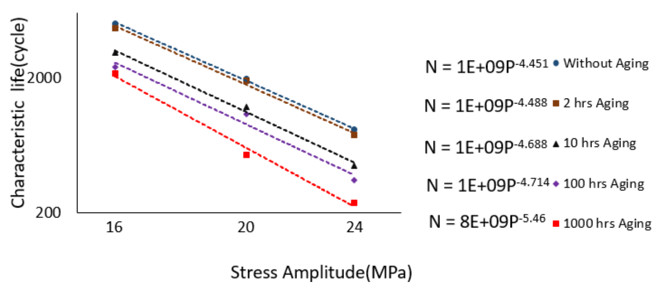


Figure 9: Characteristic life versus stress Amplitude for SAC 305 solder joints under different aging times

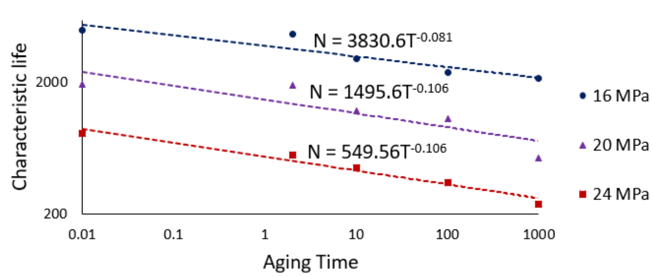


Figure 10: Characteristic life versus aging time for SAC305 solder joints under different stress Amplitudes

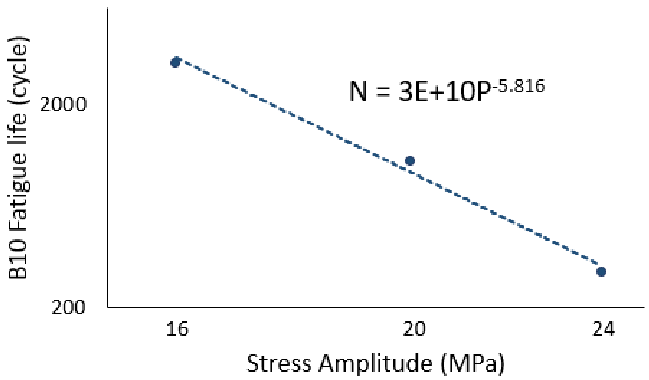


Figure 11: B10 versus stress Amplitude for SAC 305 solder joints without aging

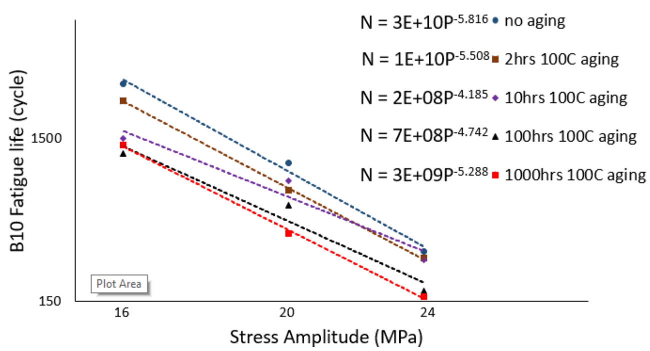


Figure 12: B10 versus stress Amplitude for SAC 305 solder joints under different aging times

Inelastic Work and Plastic Strain:

To exhibit the effect of aging time and stress amplitude on the inelastic work which is the amount of work that is required to form a crack in the solder joint and the plastic strain, the hysteresis loops for SAC305 solder joints at different stress amplitudes and aging times were initiated. Figure 13 illustrates the relationship between the strain and the applied stress for the SAC305 solder joint without aging at 16 MPa stress amplitude. MATLAB software was utilized to calculate the inelastic work which represents the area of the hysteresis loop and plastic strain. To define the steady state region which is the region for determining the average inelastic work per cycle, the fatigue life and the inelastic work per cycle are plotted. Figure 14 displays three regions of the inelastic work per cycle for SAC305 solder joint without aging cycled at 20 MPa. In the first region, the inelastic work spectacles a fast decreasing. On the other hand, the second region represents a stability of the inelastic work which is called the steady-state region and represents 90% of total life cycles. The third region shows an increase in the inelastic work until failure. In the steady state region, the hysteresis loops for SAC305 solder joints without aging at different stress amplitudes were plotted in Figure 15. Figure 15 demonstrates an increase in the inelastic work per cycle and plastic strain when the stress amplitude was increased. The slope of the relationship between the growing extensions and the stress amplitude is the same at the different stress amplitudes. To exhibit the effect of aging time on the work per cycle and plastic strain, the hysteresis loops at different aging times and stress amplitudes are found. Figure 16 shows the hysteresis loops for SAC305 solder joints for different aging times at 16 MPa stress amplitude. From the analysis of the hysteresis loops for SAC305 solder joint for different aging times at certain stress, the accretion in the plastic strain and inelastic work when the aging time was increased is noted.

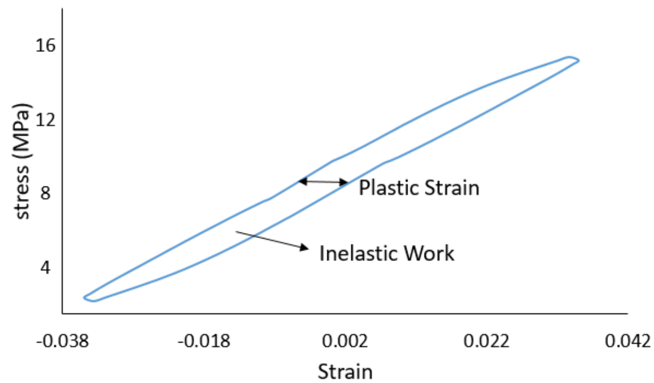


Figure 13: The full hysteresis loop for SAC305 solder joints without aging at 16 MPa stress amplitude.

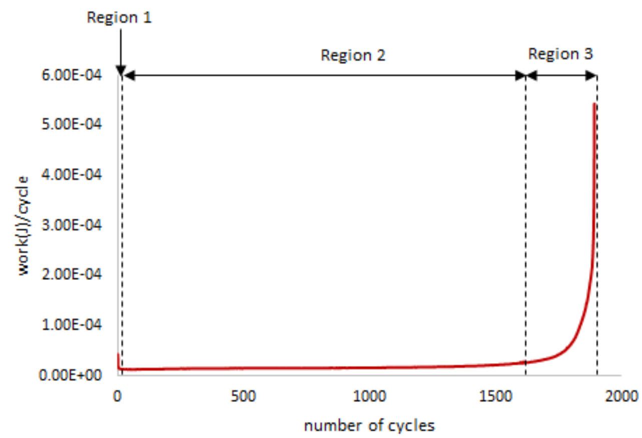


Figure 14: Inelastic work versus the number of cycle for SAC305 solder joints without aging cycled at 20 MPa stress amplitude.

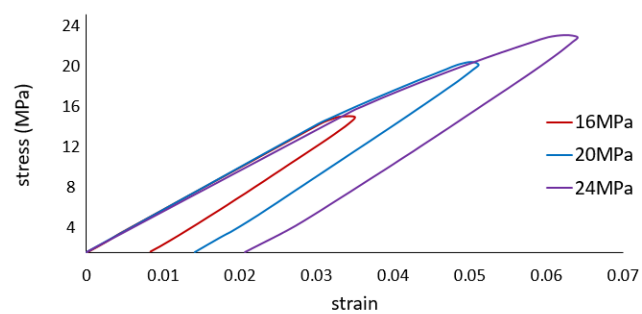


Figure 15: The hysteresis loops for SAC305 solder joints without aging in the steady state region for different stress amplitudes.

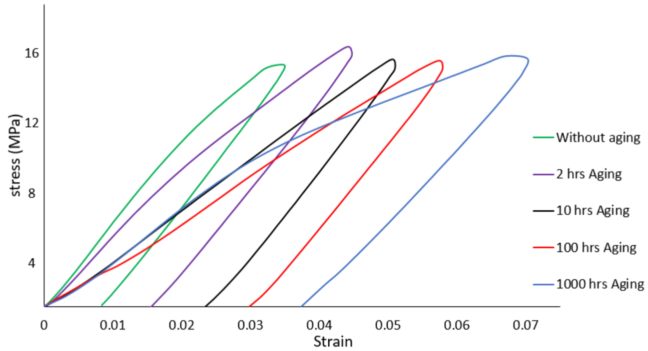


Figure 16: The hysteresis loops for SAC305 solder joints in the steady-state region for different aging times at 16 MPa stress amplitude.

Prediction Model for the Inelastic Work and Plastic Strain:

To construct a model for predicting the inelastic work per cycle as a function of aging time, the relationships between the aging time and the average inelastic work per cycle with its fitting equations at different stress amplitudes are illustrated in Figure 17 in log-log scale plots. The higher inelastic work per cycle is found when the solder joints have higher aging time, and the increase in inelastic work per cycle when the stress amplitude is increased is demonstrated. From these fitting equations, the inelastic work per cycle can be determined at any aging time when the solder joints are cycled at certain stress where W is the inelastic work per cycle and T is the aging time. The relationships between the aging time and the plastic strain for the solder joint at different aging times and stress amplitudes are shown in Figure 18 in log-log scale plot. The results show that higher plastic strain has a lower aging time and the growth in the plastic strain is started when the stress amplitude is increased. In order to initiate prediction equations for the plastic strain at different aging times and stress amplitudes, power equations are implemented to fit the trends between the plastic strain and the aging time as shown in Figure 18 where S is the plastic strain and T is the aging time. As a result, from the plastic stain and the inelastic work per cycle analysis, a set of equations were defined to estimate the inelastic work per cycle and plastic strain at different aging times when the solder joints are cycled at a certain stress amplitude.

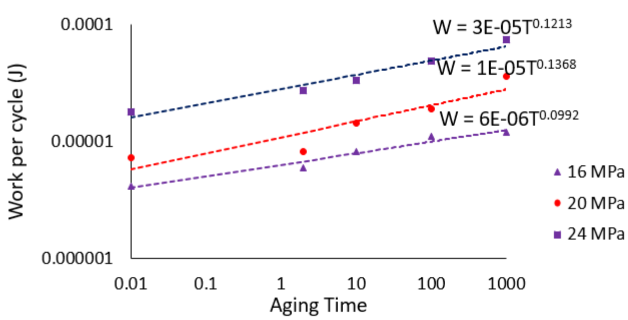


Figure 17: Inelastic work per cycle versus aging time for SAC305 solder joints at different stress amplitudes

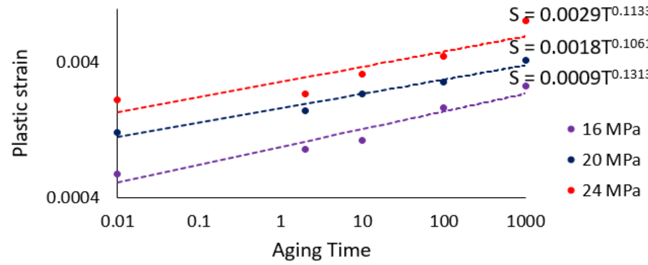


Figure 18: Plastic versus aging time for SAC 305 solder joints at different stress amplitudes

CONCLUSION

This paper studied the reliability of lead-free solder joints SAC305 with OSP surface finish under different aging conditions and cyclic shear stress amplitudes. Isothermal accelerated fatigue shear test was utilized to demonstrate the reliability of the solder joint. The aging temperature was 100ºC and four different aging times were implemented (2 hrs, 10 hrs, 100 hrs, and 1000 hrs) under three different cyclic shear stress amplitudes (16 MPa, 20 MPa, and 24 MPa). Two-parameter Weibull distribution was utilized to assess the reliability of the solder joint at each service condition. The results show a reduction in the fatigue life when the cyclic shear stress amplitude has higher value and an increase in the fatigue life when the aging time has a lower value. The relationship between the stress amplitude and the characteristic life was identified. The fitted power equations that relate them were determined for each aging time and the fitted power equations that relate aging time and characteristic life were built for each stress amplitude. Prediction reliability models to predict the characteristic life were constructed as a function of the stress amplitude and aging time. The model is obtained by calculating the average of the shape parameters and using the relationships between the fatigue life, stress amplitude and aging times. The earlier failures that are associated with SAC305 solder joint at different stress amplitudes sand aging times were studied as well. B10 was used to represent the earlier failure. The relationships between the B10 and stress amplitude at different aging times and its fitted prediction equations were formulated. In order to predict the inelastic work per cycle and the plastic strain, the steady state region was defined. To determine the inelastic work and plastic strain, the hysteresis loops at different aging times and stress amplitudes were demonstrated. The relationships between the aging time, the inelastic work per cycle and plastic strain were obtained, and the power equation was utilized to form a set of fitted prediction equations. As a result from this analysis, a model form from a set of fitted equations was originated as a function of aging time and stress amplitude to predict the fatigue life, inelastic work, and plastic strain.

FUTURE WORK

As an extension to this work, the reliability of solder joints SAC305 with OSP surface finish with different aging temperatures will be studied, and another reliability model will be constructed as a function of the aging temperature, work per cycle, plastic strain, stress amplitude and aging time. The reliability of other types of solder joints and surface finishes may be studied to construct the reliability model for each combination to facilitate the process of demonstrating the optimal alternative.

REFERENCES

1. Ma, H., Suhling, J. C., Lall, P., & Bozack, M. J. (2006, May). Reliability of the aging lead-free solder joint. In *Electronic Components and Technology Conference, 2006. Proceedings. 56th* (pp. 16-pp). IEEE.

2. Su, S., Fu, N., & Akkara, F. J. (2018). Effect of Long-Term Room Temperature Aging on the Fatigue Properties of SnAgCu Solder Joint. *Journal of Electronic Packaging*.

3. Borgesen, P., Hamasha, S., Wentlent, L., Watson, D., & Greene, C. (2016, January). Interpreting accelerated test results for lead-free solder joints. In *Pan Pacific Microelectronics Symposium (Pan Pacific), 2016* (pp. 1-9). IEEE.

4. Zhang, Jiawei, et al. "Thermal aging effects on the thermal cycling reliability of lead-free fine pitch packages." *IEEE transactions on components, packaging and manufacturing technology* 3.8 (2013): 1348-1357.

5. Tsui, Y. K., Lee, S. R., & Huang, X. (2002, December). Experimental investigation on the degradation of BGA solder ball shear strength due to room temperature aging. In *Electronic Materials and Packaging, 2002. Proceedings of the 4th International Symposium on* (pp. 478-481). IEEE.

6. Ma, H., & Suhling, J. C. (2009). A review of mechanical properties of lead-free solders for electronic packaging. *Journal of materials science, 44*(5), 1141-1158.

7. Coyle, R. J., Solan, P. P., Serafino, A. J., & Gahr, S. A. (2000). The influence of room temperature aging on ball shear strength and microstructure of area array solder balls. In *Electronic Components & Technology Conference, 2000. 2000 Proceedings. 50th* (pp. 160-169). IEEE.

8. Lee, T. K., Ma, H., Liu, K. C., & Xue, J. (2010). Impact of isothermal aging on long-term reliability of fine-pitch ball grid array packages with Sn-Ag-Cu solder interconnects: Surface finish effects. *Journal of Electronic Materials, 39*(12), 2564-2573.

9. Smetana, J., Coyle, R., Read, P., Popowich, R., Fleming, D., & Sack, T. (2011, October). Variations in thermal cycling response of Pb-free solder due to isothermal preconditioning. In *Proceedings of the 2011 SMTAI Conference* (pp. 641-654).

10. Zhang, Y., Cai, Z., Suhling, J. C., Lall, P., & Bozack, M. J. (2008, May). The effects of aging temperature on SAC solder joint material behavior and reliability. In *Electronic Components and Technology Conference, 2008. ECTC 2008. 58th* (pp. 99-112). IEEE.

11. Li, L., Jang, J. W., & Allmen, B. (2001). Shear property and microstructure evaluation of Pb-free solder bumps under room temperature and multiple reflow/high temperature aging. In *Advanced Packaging Materials: Processes, Properties and Interfaces, 2001. Proceedings. International Symposium on* (pp. 347-353). IEEE.

12. Zhang, J., Hai, Z., Thirugnanasambandam, S., Evans, J. L., Bozack, M. J., Zhang, Y., & Suhling, J. C. (2013). Thermal aging effects on the thermal cycling reliability of lead-free fine pitch packages. *IEEE transactions on components, packaging and manufacturing technology, 3*(8), 1348-1357.

13. Su, S., Akkara, F., Dawahdeh, A., Borgesen, P., & Qasaimeh, A. (2017, May). Solder joint reliability in isothermal varying load cycling. In *Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2017 16th IEEE Intersociety Conference on* (pp. 1331-1336). IEEE.

14. Lall, P., Shantaram, S., Suhling, J., & Locker, D. (2013, May). Effect of aging on the high strain rate mechanical properties of SAC105 and SAC305 leadfree alloys. In *Electronic Components and Technology Conference (ECTC), 2013 IEEE 63rd* (pp. 1277-1293). IEEE.

15. Han, Y. D., Jing, H. Y., Nai, S. M. L., Xu, L. Y., Tan, C. M., & Wei, J. (2010). Temperature dependence of creep and hardness of Sn-Ag-Cu lead-free solder. *Journal of Electronic Materials, 39*(2), 223-229.

16. Venkatadri, V., Yin, L., Xing, Y., Cotts, E., Srihari, K., & Borgesen, P. (2009, May). Accelerating the effects of aging on the reliability of lead-free solder joints in a quantitative fashion. In *Electronic Components and Technology Conference, 2009. ECTC 2009. 59th* (pp. 398-405). IEEE.

17. Hasnine, M., Mustafa, M., Suhling, J. C., Prorok, B. C., Bozack, M. J., & Lall, P. (2013, May). Characterization of aging effects in lead-free solder joints using nanoindentation. In *Electronic*

Components and Technology Conference (ECTC), 2013 IEEE 63rd (pp. 166-178). IEEE.

18. Chuang, C. M., Lui, T. S., & Chen, L. H. (2002). Effect of aluminum addition on tensile properties of naturally aged Sn-9Zn eutectic solder. *Journal of Materials Science, 37*(1), 191-195.

19. Andersson, C., Lai, Z., Liu, J., Jiang, H., & Yu, Y. (2005). Comparison of isothermal mechanical fatigue properties of lead-free solder joints and bulk solders. *Materials Science and Engineering: A*, *394*(1-2), 20-27.

20. Zhang, Y., Cai, Z., Suhling, J. C., Lall, P., & Bozack, M. J. (2009, May). The effects of SAC alloy composition on aging resistance and reliability. In *Electronic Components and Technology Conference, 2009. ECTC 2009. 59th* (pp. 370-389). IEEE.

21. Chilton, A. C., Whitmore, M. A., & Hampshire, W. B. (1989). Fatigue failure in a model SMD joint. *Soldering & Surface Mount Technology*, *1*(3), 21-24.

22. Charles, E. E. (2008). An introduction to reliability and maintainability engineering. *TsingHua and McGraw-Hill Education, Beijing*.