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Shear Strength Degradation Modeling of Lead-Free Solder Joints at Different Isothermal Aging Conditions

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***Abstract*—SAC-based alloys are one of the most common solder materials that are utilized to provide mechanical support and electrical connection between electronic components and the printed circuit board. Enhancing the mechanical properties of solder joints can improve the life of the components. One of the mechanical properties that define the solder joint structure integrity is the shear strength. The main objective of this study is to assess the shear strength behavior of SAC305 solder joints under different aging conditions. Instron 5948 Micromechanical Tester with a customized fixture is used to perform accelerated shear tests on individual solder joints. The shear strength of SAC305 solder joints with organic solderability preservative (OSP) surface finish is investigated at constant strain rate under different aging times (2, 10, 100, and 1,000 h) and different aging temperatures (50, 100, and 150°C). The nonaged solder joints are examined as well for comparison purposes. Analysis of variance (ANOVA) is accomplished to identify the contribution of each parameter on the shear strength. A general empirical model is developed to estimate the shear strength as a function of aging conditions using the Arrhenius term. Microstructure analysis is performed at different aging conditions using scanning electron microscope (SEM). The results revealed a significant reduction in the shear strength when the aging level is increased. An increase in the precipitates coarsening and intermetallic compound (IMC) layer thickness are observed with increased aging time and temperature.**

***Keywords*—SAC305, shear strength, aging, lead-free**

INTRODUCTION

Electronic devices are exposed to different types of mechanical and thermal stresses in actual operating conditions, e.g., thermal cycling, thermal shock, vibration, mechanical shock, and erosion. Solder joints are subject to a combination of shear and tensile stresses due to being exposed to harsh environmental conditions. The cyclic change in the operating temperature leads to expose the solder joints to shear stress in different directions because of the mismatch between the coefficients of the thermal expansion of the solder joints, Printed Circuit Board (PCB), and the packaging assemblies. Solder joints are frequently exposed to certain levels of aging from the thermal cycling process, working in high temperature environmental conditions or storing the electronic assemblies over the shelves for a long time [1–7]. Aging significantly affects the microstructure of the solder joints, which leads to a major evolution on the mechanical and fatigue properties of the solder joints [8–15]. In this study, the shear strength of SAC305 solder joints was investigated under different levels of aging in actual setting conditions.

Several studies explored the fatigue and mechanical properties of SAC-based solder joints under different operational conditions. Alathamneh et al. investigated the effect of aging time on the fatigue properties of SAC305 solder joints. A general reliability model was developed to predict the fatigue life of the solder joint as a function of the cyclic stress amplitude and aging time [16]. Lau investigated the thermal, vibrational, and mechanical behavior of the plastic ball grid array and flip chip. The thermal response was evaluated by using the fracture mechanics methods, nonlinear finite element, and Coffin–Manson model [17]. Darveaux and Banerji developed a method for predicting the fatigue life of the flip chip bonds under different thermal cycling conditions by utilizing the finite element simulation and Coffin–Manson model [18]. Rajendran et al. in their study studied the characteristics of Sn-3.0Ag-0.5Cu (SAC305)/Cu joints (when ZrO2 nanoparticles were added) with respect to aging and shear strength. The results showed that coarsening of Ag3Sn and an increase in the thickness of interfacial intermetallic compound (IMC) layer was observed, which in turn lead decrease the shear strength of the solder joints [19].

Wu et al. did a comparative study of SAC305 and SAC_Q solder joints for their microstructure evolution and mechanical aging. The authors found that better high temperature mechanical properties such as ultimate strength, effective modulus, and creep resistance were more dominant in SAC-Q solder joints when compared with SAC305. The material degradation and microstructure were also large for SAC305 solder joints and found to be correlated with the increase of the average IMC particle diameter [20]. Bao et al. investigated the mechanical reliability and microstructure evolution for transient liquid phase (sintered joint) under thermal aging. Their experiment verified the high reliability of the transient liquid phase sintered joint with SAC307_Ag powders [21]. Xiong et al. studied the behavior of Sn-Ag-Cu lead-free solder joints as a result of interface reaction and IMC growth. The study showed that the IMC growth is inhabited under the addition of RE elements, oxide particles, graphene nanoparticles, and metal particles. This growth led to improve the reliability of Sn-Ag-Cu lead-free solder joints [22]. Wu et al. examined the microstructural changes for aging induced SAC + Bi (SAC_Q) lead-free solder and found that after

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reflow solidification, rich phases Bi were present in SAC_Q solder joints. Ag3Sn intermetallic compound coarsening was highly prominent in SAC-Q solder joints when compared with SAC305 solder joints [23]. The effect of aging time on the shear strength and microstructure evolutions were investigated by Sundelin et al. a negative relationship between the amount coarsening in the precipitates due to aging and the shear strength was observed [24].

According to the presented literature, most of the studies tried to extract the mechanical properties of the solder joints by applying the mechanical tests on the electronic package body. Using these types of tests with the current setup could lead to a wrong conclusion about the mechanical behaviors because of the major differences for the different types of packages in terms of package design, used materials, size and load distribution, and interaction with other stresses. On the other hand, there are limited number of studies that attempted to investigate the mechanical properties of the individual solder joints at actual setting conditions and different operating conditions. In this study, a special experimental setup was used to explore the shear strength behavior of individual lead-free solder joints at actual setting conditions and different aging levels. The effects of four levels of aging time and three levels of aging temperature on individual SAC305 solder joints were investigated and compared with nonaged solder joints. The main contribution for this study is to use a special experimental setup to perform the shear test on individual solder joints in actual setting conditions. A general prediction model of the shear strength is constructed as a function of aging time and temperature by utilizing the Arrhenius model and empirical models. Analysis of variance (ANOVA) for the effect of aging conditions on the shear strength was performed as well. Microstructure analysis is performed at different aging conditions to elaborate the evolutions in the shear strength with the major changes in the solder joint microstructure due to aging.

MATERIALS AND EXPERIMENTAL SETUP

The testing material used in this study is SAC305 solder. The employed surface finish is Organic solderability preservative (OSP) surface finish. The FR-4 glass epoxy with full array for the solder balls (144 solder joints) is used to design the testing board. Fig. 1 illustrates the testing board layout. The dimension for the solder joint diameter is 30 mil and the pitch distance between the solder ball is 3 mm. The opening copper pads 22 mil is utilized for the solder mask defined in the experiment. Two stencils were used to fabricate the testing board with different diameters. Printing the tacky flux on the PCB was performed by one stencil and the second stencil is used for applying the solder ball on top of the flux. Instron 5948 micro tester machine was used to implement the shear test. To perform the shear test on the individual solder joints at actual operating conditions, a special fixture was manufactured and designed. The configurations between the solder joint, testing fixture, and testing machine are illustrated in Fig. 2.

RESULTS AND ANALYSIS

This study aims at investigating the effect of aging on the shear strength of SAC305 solder joints in actual operating setting and constructing the prediction model of the shear strength. Table I represents the test matrix of the shear test. A strain rate of 0.1^{-1}S was utilized in the study. Fig. 3 shows the stress–strain curve for SAC305 solder joints without aging. The ultimate shear strength of the solder joints is used to display its shear strength of the solder joints. Figs. 4 and 5 demonstrate the effects of aging time and temperature on the shear strength of the solder joints, respectively. Results indicated that a reduction in the shear strength is observed with increasing the aging temperature or the aging time. The reduction in the shear strength is found to be exponentially decreasing with aging time for the short-term aging. Linear behavior of the long-term aging effect is noticed for the reduction in the shear strength. Arrhenius model is one of the famous models that is used to describe the effect of working temperature on the mechanical and fatigue properties of the metals. The Shear strength is decreased with increasing aging temperature and the Arrhenius model, shown in eq. (1), is used to describe and estimate the shear strength reduction due to the increase in the aging temperature [25].

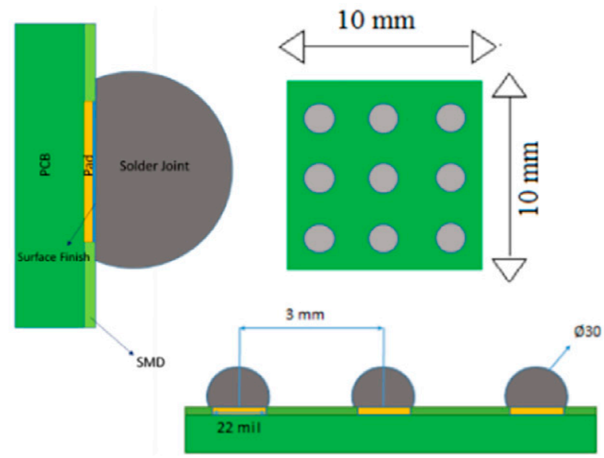

Fig. 1. The testing Board.

$$f = C * e^{-\frac{M}{T}} \tag{1}$$

where T represents the aging temperature, C and M are constants and f is the process rate. A summary of the shear test results is represented in Fig. 6. A reduction in the shear strength was found to be the largest in the solder joint that was aged for 1,000 h at 150°C aging temperature. The averages of the reduction in shear strength of the solder joints that are aged for 2, 10, 100, 1,000 h compared with the nonaged solder joints are 3.2%, 6.9%, 14.2%, and 17.1%, respectively. The means of the drop in the shear strength of the solder joints at 50°C, 100°C, and 150°C aging temperature were 8%, 10.25%, and 12.8%, respectively. The effect of aging time is accelerated when the solder joint is aged at elevated temperatures. The evolutions in the shear strength were bigger when the solder joints were aged at 150°C compared with 100°C. The reduction in the shear strength for the solder joints was magnified at 100 h compared with other levels of aging time. The average in the reduction of the shear strength for the solder joints that are aged for 100 h aging is 7.3% when compared with 10 h aging. On the other hand, the average of the reduction in the shear strength for the solder joints that are aged for 1,000 h is 2.93% when compared with 100 h aging.

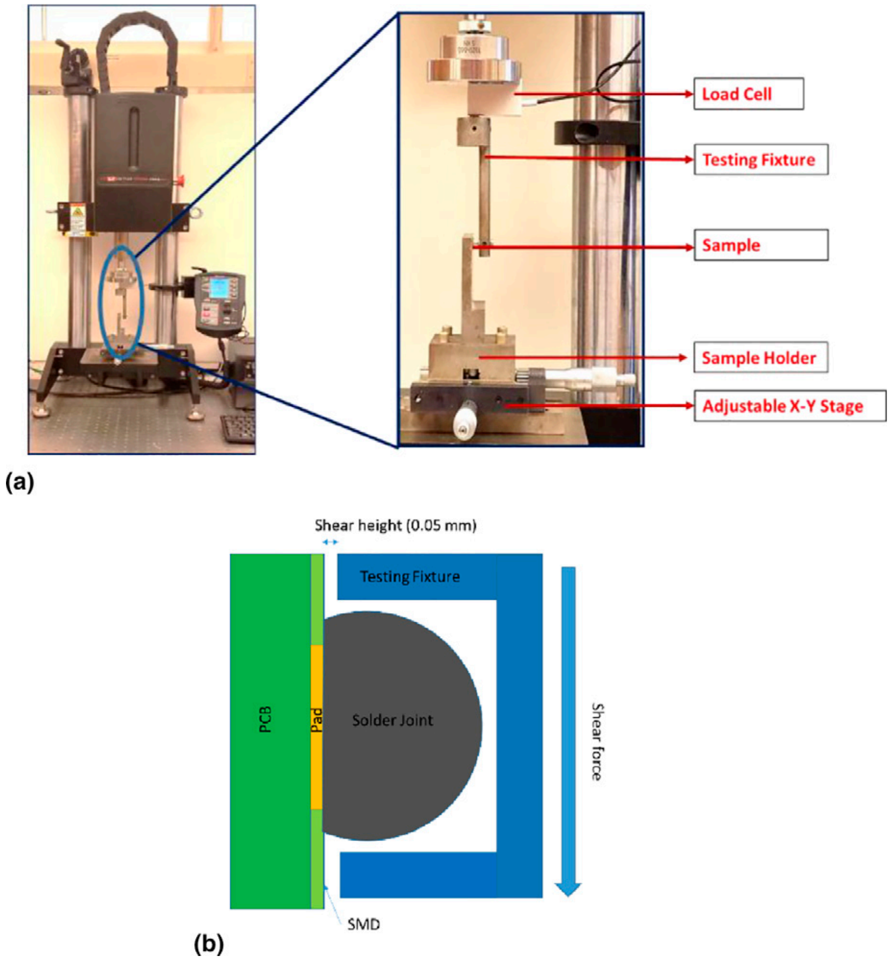

Fig. 2. (a) The instron testing machine and (b) the fixture configurations.

Table I
Test Matrix for the Shear Test

Aging temperature (°C)	Aging time (h)				
	Non-aged	2	10	100	1000
50	7 Joints	7 Joints	7 Joints	7 Joints	7 Joints
100		7 Joints	7 Joints	7 Joints	7 Joints
150		7 Joints	7 Joints	7 Joints	7 Joints

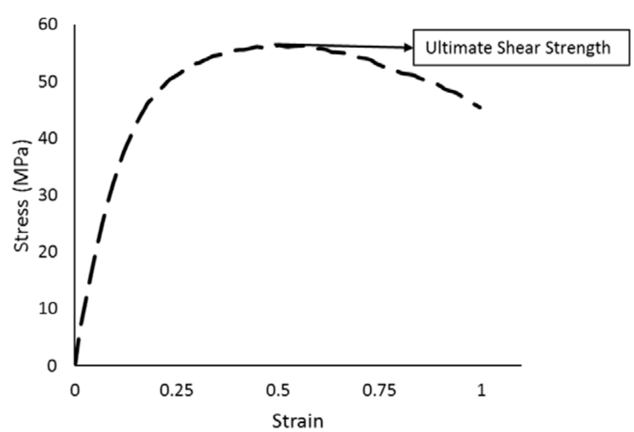

Fig. 3. The stress–strain curve for the nonaged SAC305 solder joints.

Fig. 7 shows the Arrhenius equations for the effect of aging temperature on the shear strength for the SAC305 solder joints at different aging times in real operating conditions. As a conclusion from Fig. 7, the Arrhenius equation constants are influenced with the increase in aging time. Therefore, the Arrhenius model that describe the effect of aging temperature on the shear strength of the solder joints is not valid for the specimens that are aged for different times. This phenomenon represents the needs of exploring the effect of aging time on the Arrhenius model. To represent the effect of aging time in the first hours, an exponential term is applied and to describe the long-term aging, a linear term is employed. The suggested prediction model for the effect of aging time on the shear strength of individual SAC 305 solder joints at actual operating conditions is shown in eq. (2). A general empirical equation (eq. (3)) was utilized as a fitted equation of the relationship between the aging conditions and the shear strength to construct a prediction model of the shear strength as a function of aging conditions. Where *SS* is the shear strength of the solder joints, *T* is the aging temperature, *t* is the aging time, and k_1–k_6 are equation constants. To illustrate the effect of aging temperature,

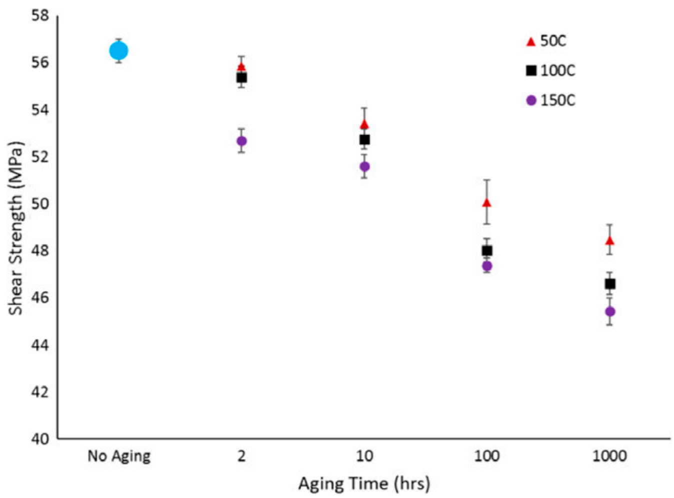

Fig. 4. The effect of aging time on the shear strength of the solder joints.

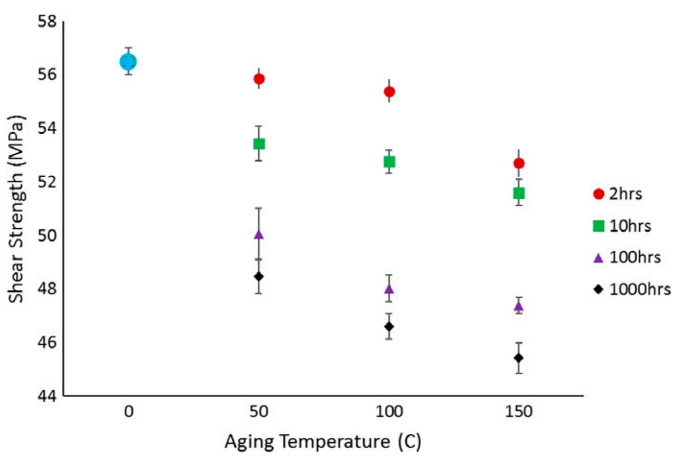

Fig. 5. The effect of aging temperature on the shear strength of the solder joints.

Arrhenius model is used [24]. Eq. 4 shows the final shear model that is found by using a nonlinear optimizer. The R-squared value for the attained model is 98%.

$$SS = \underbrace{K_1 + K_2 \times e^{t \times k_3} + t \times k_4}_{\text{Aging time term}} \tag{2}$$

$$SS = \underbrace{K_1 + K_2 \times e^{t \times k_3} + t \times k_4}_{\text{Aging time term}} + \underbrace{K_5 \times e^{\frac{-K_6}{T}}}_{\text{Arrhenius term}} \tag{3}$$

$$SS = 56.5 + 0.0021 \times e^{t \times 0.01} - t \times 7.14 - 97.88 \times e^{\frac{-0.056}{T}} \tag{4}$$

To determine the effect and the contribution of the aging conditions on the shear strength and the level of significance for each of the aging factors, the ANOVA was performed, Table II shows the analysis results. Figs. 8 and 9 show the main effect and the interaction plot for the effect of aging temperature and aging time on the shear strength. The aging time and temperature have a significant impact on the shear strength reduction. The contribution of aging time on Ultimate Tensile Strength (UTS) value that is represented by the slope of the curve is higher than the aging temperature contribution. The ANOVA analysis revealed a significant effect for the both the aging temperature and the aging time on the shear strength of the solder joints. The contribution of the aging time on the shear strength was larger than the contribution of the aging temperature (53.5% compared with 16.6%). Fig. 9 shows the interaction effect between the aging temperature and aging time on the shear strength of the solder joints. The interaction effect was nonsignificant at 95% confidence level that can be observed from the ANOVA analysis and Fig. 9 for the interaction plots. However, the contribution of the interaction between the aging factors on the shear strength of SAC305 solder joints is still significant at 90% confidence level where the P value and contribution percentage are 0.09% and 6%, respectively.

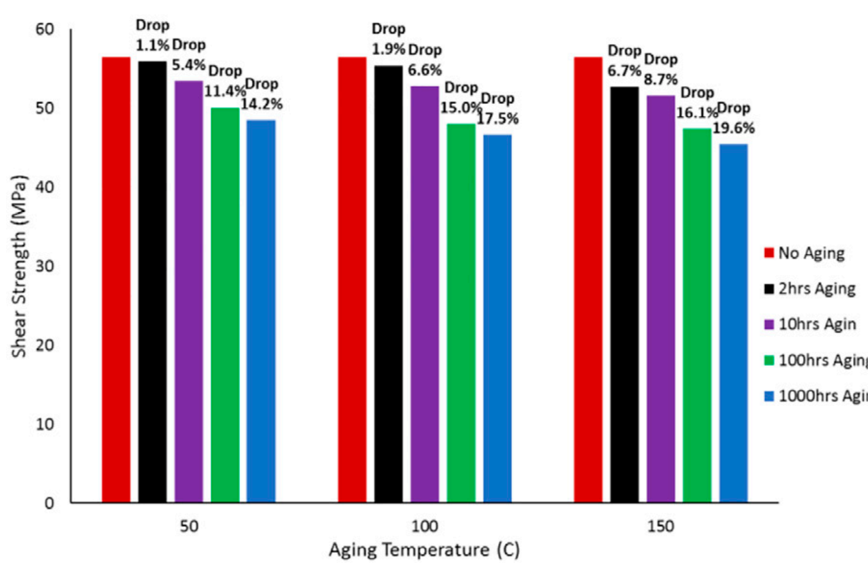

Fig. 6. Summary of the data for the shear strength at different aging conditions.

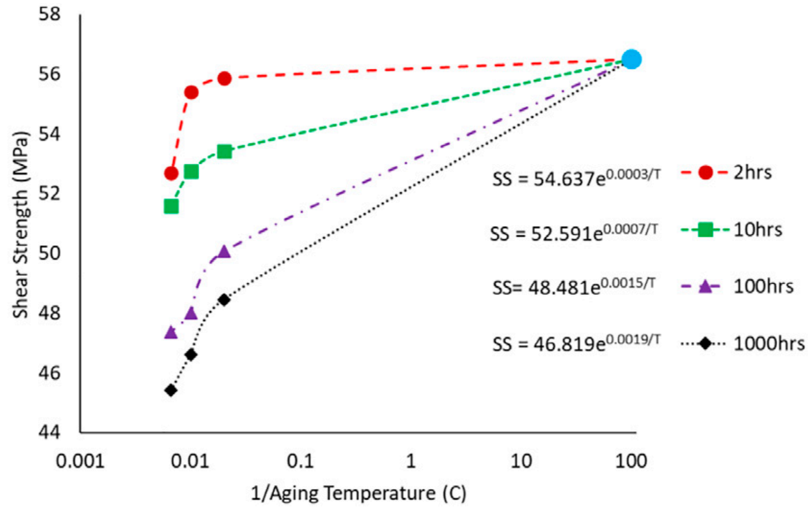

Fig. 7. Arrhenius equations at different aging times for the shear strength of SAC305 solder joints.

Table II
ANOVA Analysis for the Effects of Aging Time and Temperature on the Solder Joints Shear Strength

Source	DF	Contributions	Adj SS	Adj MS	F-value	*P* value
Regression	7	70.1%	1,362.6	194.7	27.7	<.0001
Aging time	4	53.5%	1,040.7	260.2	37.1	<.0001
Aging temperature	3	16.6%	321.9	107.3	15.3	<.0001
Error	83		582.6	7.0		
Total	90		1,945.2			

MICROSTRUCTURE ANALYSIS

The microstructure analysis in necessary to figure out the various causes behind the shear strength reduction of SAC305 solder joints because of aging. The microstructure images were captured using the scanning electron microscope (SEM) with an applied magnification level of 5,000 K. The microstructure analysis was performed for solder joints aged at different levels of aging temperature and time. Grinding and polishing were both performed at four stages for the SAC305 solder joints mounted in epoxy. After that, the gold coating is applied for SEM microstructure preparation. An increase in the IMC layer and precipitates coarsening was observed for the aged solder joints. The shear strength reduction was influenced by the increase in precipitates coarsening. Fig. 10 illustrates the increase in the IMC layer thickness and precipitates coarsening when solder joints are aged for more time at 100°C aging temperature. Brittleness of the solder joints was increased because of the increase in IMC layer thickness with aging, which also leads to increase the brittleness behavior of the strength of the

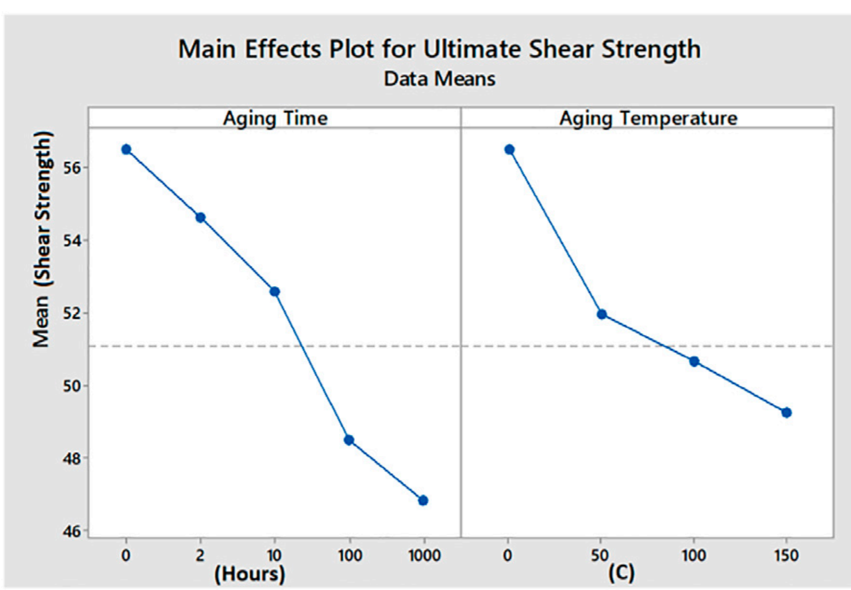

Fig. 8. The main effect plot of the solder joints shear strength with different aging conditions.

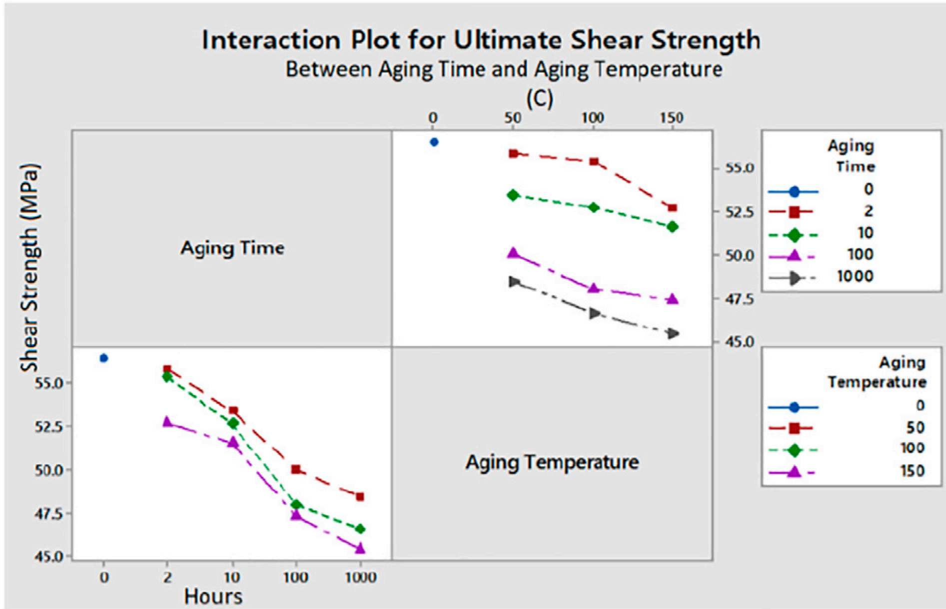

Fig. 9. The interaction plot of the solder joints shear strength with different aging conditions.

solder joints. Movement of crystalline imperfections leads to a permanent deformation in the solder alloys, which is called dislocation. Improving the strength of the solder joint can be achieved by reducing the dislocation movement. The reduction in the dislocation movements can be obtained by decreasing the grain size, which leads to increase the ratio of grain boundaries to dislocations or facing precipitates in their ways to block these movements. The small and spread distributed precipitates lead to block the dislocation move through the grain where that is associated with crack propagation and leads to high strength values. Precipitates coarsening as a result of aging changes the precipitates distribution to be larger and closer to others. This phenomenon has a high impact on the shear strength, which is decreased with aging. The presented results in this study are clearly supporting these phenomena. From the observed samples, the aging condition did not change the failure mode. Bulk solder failures were found for all tested samples regardless to the amount of exposed aging.

Fig. 11 shows the evolutions in IMC layer growth at different aging temperatures at a fixed aging time (100 h). As a result of comparing Figs. 10 and 11, the growth in IMC layer was highly impacted by aging time compared with aging temperature for the

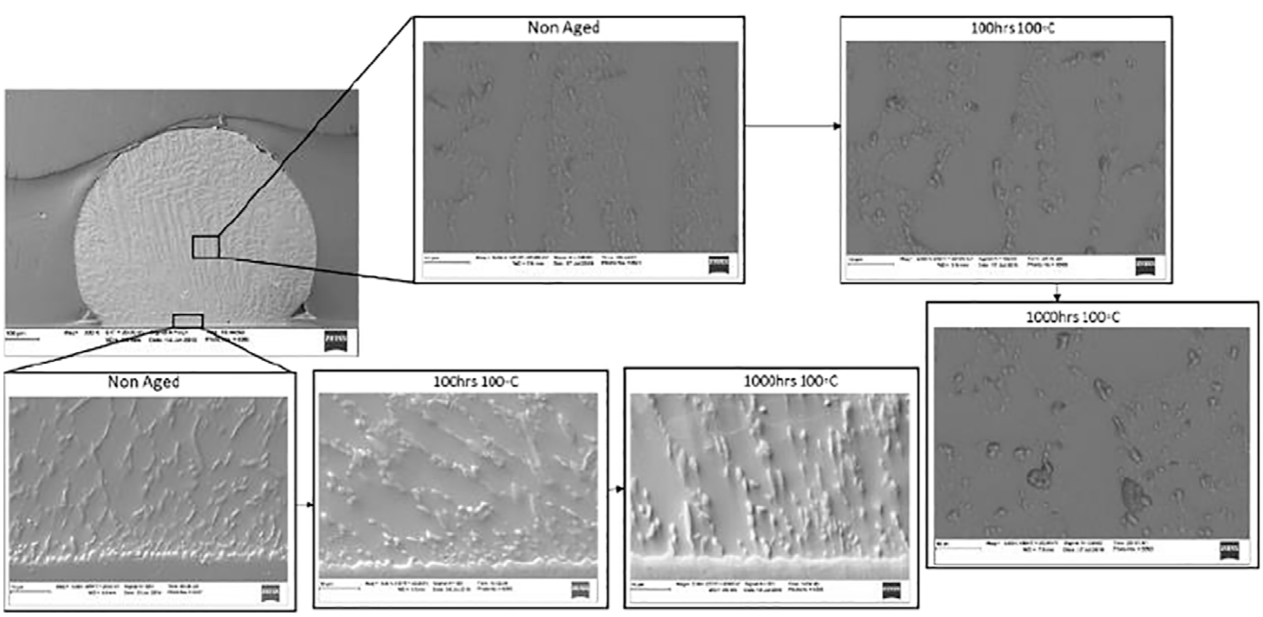

Fig. 10. The precipitates coarsening in SAC305 solder joints at different aging times.

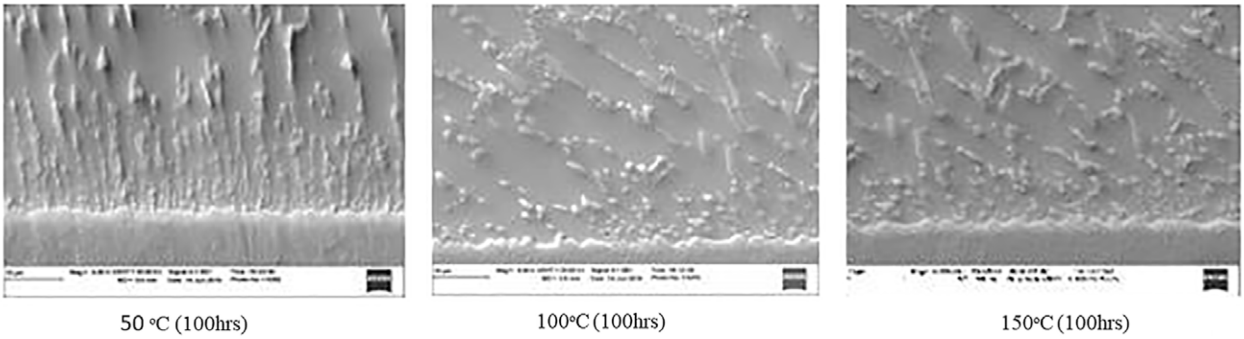

Fig. 11. IMC layer growth at different aging temperatures.

studied levels. Fig. 12 represents the typical break surfaces for the SAC305 solder joins at different conditions. No systematic evolutions on the shape of the breaking surface were observed when the testing conditions were changed.

CONCLUSION

This study investigated the effect of changing the aging temperature and time on the shear strength degradations for SAC305 solder joints in real operating conditions. The Arrhenius model and empirical model were used to illustrate the degradations on the shear strength. ANOVA analysis was performed to investigate the contribution of the aging time and temperature on the shear strength of the solder joints. The effect of the short and long terms aging times are modeled using exponential and linear functions, respectively. Moreover, the Arrhenius model is utilized to describe the effect of aging temperature. The contribution of the aging time (53.5%) on the shear strength was significantly larger compared with the effect of the aging temperature (16.6%). The ANOVA analysis and main effect plots support that. Finally, a general empirical equation is constructed to estimate the shear strength of the SAC305 solder joints under different aging conditions. The microstructure analysis was performed using SEM microscope to monitor the evolutions in the microstructure with aging. An increase in the IMC layer thickness and precipitates coarsening were observed with aging. The shear strength was significantly decreased by increasing the aging. The largest relative drop in the shear strength according to the aging time was found between 10 h and 100 h for all aging temperature levels. In contrast, there are no abnormal gaps of drop in the shear strength observed between aging temperature levels. The largest drop percentage (19.6%) at different levels of aging was determined at a combination of 150°C aging temperature and 1,000 h aging time.

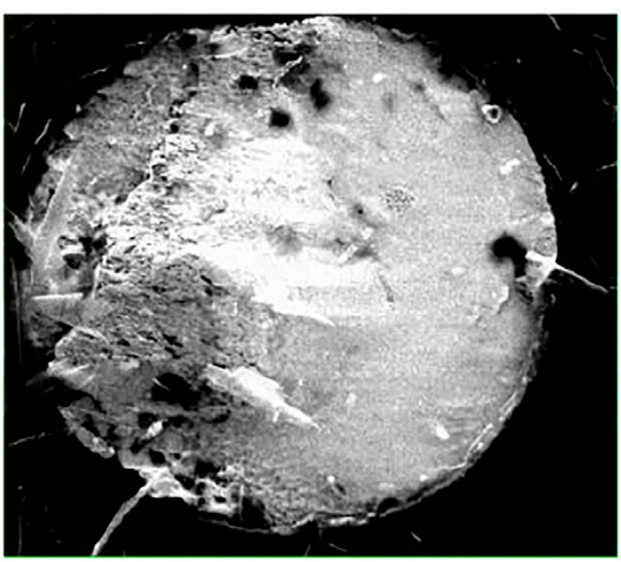

Fig. 12. The typical break surface of the solder joints.

REFERENCES

[1] L. Yang, L. Zhu, Y. Zhang, P. Liu, N. Zhang, S. Zhou, and L. Jiang, "Microstructure and reliability of Mo nanoparticle reinforced Sn–58Bi-based lead-free solder joints," *Materials Science and Technology*, Vol. 34, No. 8, pp. 992–1002, 2018.

[2] R. Al Athamneh, M. Abueed, D.B. Hani, S. Su, J. Suhling, and P. Lall, "Effect of aging on the fatigue life and shear strength of SAC305 solder joints in actual setting conditions," 2019 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), pp. 1146–1154, Las Vegas, NV, May 2019.

[3] J. Wang, S. Xue, P. Zhang, P. Zhai, and Y. Tao, "The reliability of lead-free solder joint subjected to special environment: a review," *Journal of Materials Science Materials in Electronics*, Vol. 30, No. 10, pp. 9065–9086, 2019.

[4] C.M. Shin, M.A.A.M. Salleh, and D.S.C. Halin, "Influence of thermal aging on lead-free solder joints reliability: a review," IOP Conference Series: Materials Science and Engineering, Vol. 864, No. 1, p. 012183, 2020.

[5] D. Herkommer, J. Punch, and M. Reid, "Constitutive modeling of joint-scale SAC305 solder shear samples," *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, Vol. 3, No. 2, pp. 275–281, 2012.

[6] J. Han, S. Tan, and F. Guo, "Study on subgrain rotation behavior at different interfaces of a solder joint during thermal shock," *Journal of Electronic Materials*, Vol. 45, No. 12, pp. 6086–6094, 2016.

[7] T.Y. Park, J.C. Park, and H.U. Oh, "Evaluation of structural design methodologies for predicting mechanical reliability of solder joint of BGA and TSSOP under launch random vibration excitation," *International Journal of Fatigue*, Vol. 114, pp. 206–216, 2018.

[8] Al Athamneh, R., Abueed, M., Hani, D. B., and Hamasha, S. D. "Effect of aging on SAC305 solder joints reliability in accelerated fatigue shear test," In Proc. SMTA Int. Conf.(SMTAI), Rosemont, IL, October 14–18, 2018.

[9] W. Yang, R.W. Messler, and L.E. Felton, "Microstructure evolution of eutectic Sn-Ag solder joints," *Journal of Electronic Materials*, Vol. 23, No. 8, pp. 765–772, 1994.

[10] Y. Liu, F. Sun, H. Zhang, and P. Zou, "Solderability, IMC evolution, and shear behavior of low-Ag Sn0. 7Ag0. 5Cu-BiNi/Cu solder joint," *Journal of Materials Science Materials in Electronics*, Vol. 23, No. 9, pp. 1705–1710, 2012.

[11] Y. Huang, X. Chen, F. Xue, T. Wu, W. Liu, Y. Ma, and S. Tang, "Effects of isothermal aging on interfacial microstructure evolution and shear behavior of Au-12Ge/Ni (P)/Kovar Solder Joints," *Intermetallics*, Vol. 124, p. 106865, 2020.

[12] Y. Ma, T. Wu, W. Liu, Y. Huang, S. Tang, and Y. Wang, "Interfacial microstructure evolution and shear behavior of Au–12Ge/Ni solder joints during isothermal aging," *Journal of Materials Science Materials in Electronics*, Vol. 28, No. 4, pp. 3685–3694, 2017.

[13] J. Wu, J.C. Suhling, and P. Lall, "Microstructural evolution in SAC+ X solders subjected to aging," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), pp. 1087–1098, Las Vegas, NV, May 2019.

[14] L. Sun, M.H. Chen, and L. Zhang, "Microstructure evolution and grain orientation of IMC in Cu-Sn TLP bonding solder joints," *Journal of Alloys and Compounds*, Vol. 786, pp. 677–687, 2019.

[15] R. Xu, Y. Liu, H. Zhang, Z. Li, F. Sun, and G. Zhang, "Evolution of the microstructure of Sn58Bi solder paste with Sn-3.0 Ag-0.5 Cu addition during isothermal aging," *Journal of Electronic Materials*, Vol. 48, No. 3, pp. 1758–1765, 2019.

[16] R. Al Athamneh, D.B. Hani, and H. Ali, "Reliability modeling for aged SAC305 solder joints cycled in accelerated shear fatigue test," *Microelectronics and Reliability*, Vol. 104, p. 113507, 2020.

[17] J.H. Lau, "Solder joint reliability of flip chip and plastic ball grid array assemblies under thermal, mechanical, and vibrational conditions," IEEE Transactions on Components, Packaging, and Manufacturing Technology, *Part B*, Vol. 19, No. 4, pp. 728–735, 1996.

[18] Darveaux, R., and Banerji, K. "Fatigue analysis of flip chip assemblies using thermal stress simulations and a Coffin-Manson relation," 1991 Proceedings 41st Electronic Components & Technology Conference, pp. 797–805, Atlanta, GA, May 1991.

[19] S.H. Rajendran, S.J. Hwang, and J.P. Jung, "Shear strength and aging characteristics of Sn-3.0 Ag-0.5 Cu/Cu solder joint reinforced with ZrO2 nanoparticles," *Metals*, Vol. 10, No. 10, p. 1295, 2020.

[20] J. Wu, M.S. Alam, K.R. Hassan, J.C. Suhling, and P. Lall, "Investigation and comparison of aging effects in SAC+ X solders exposed to high temperatures," 2020 IEEE 70th Electronic Components and Technology Conference (ECTC), pp. 492–503, Orlando, FL, June 2020.

[21] Y. Bao, A. Wu, H. Shao, Y. Zhao, L. Liu, and G. Zou, "Microstructural evolution and mechanical reliability of transient liquid phase sintered joint during thermal aging," *Journal of Materials Science*, Vol. 54, No. 1, pp. 765–776, 2019.

[22] M.Y. Xiong and L. Zhang, "Interface reaction and intermetallic compound growth behavior of Sn-Ag-Cu lead-free solder joints on different substrates in electronic packaging," *Journal of Materials Science*, Vol. 54, No. 2, pp. 1741–1768, 2019.

[23] J. Wu, M.S. Alam, J.C. Suhling, and P. Lall, "Investigation of the effects of high temperature aging on mechanical behavior and microstructural changes in lead free solders," International Electronic Packaging Technical Conference and Exhibition (Vol. 59322, p. V001T08A011), American Society of Mechanical Engineers, Anaheim, California, October 7–9, 2019.

[24] J.J. Sundelin, S.T. Nurmi, T.K. Lepistö, and E.O. Ristolainen, "Mechanical and microstructural properties of SnAgCu solder joints," *Materials Science and Engineering A*, Vol. 420, No. 1-2, pp. 55–62, 2006.

[25] P. Lall, "Tutorial: temperature as an input to microelectronics-reliability models," *IEEE Transactions on Reliability*, Vol. 45, No. 1, pp. 3–9, 1996.