EFFECT OF COMPONENT DENSITY ON SN-3.0AG-0.5CU SOLDER JOINT RELIABILITY UNDER HARSH ENVIRONMENT

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ABSTRACT

Due to End-of-Life Vehicle (EVL) banning, automotive electronics and its manufacturing system was exchanged, and also heavy construction equipment is demanded to use lead free electronics. Thus, in this study, degradation behavior of lead free solder joint was quantitatively compared with mounted position and component density of vehicle engine control unit (VECU) for excavator. Sn-3.0Ag-0.5Cu (SAC305) Pb-free solder and FR-4 PCB plated with electroless nickel immersion gold (ENIG) were used. Thermal shock test was performed at -40-125 ℃, 10 min dwell at each temperature for 1500 cycles. We obtained that shear strength degradation of high component density area was larger than that of small component density. Based on this result, we have known that it was important to consider the component density for uniform heat distribution at electric circuit design under harsh environment.

Key words: Component density, Thermal cycling, Pb-free, Solder joint, Degradation, Automotive electronics

INTRODUCTION

A proportion of car electronics in vehicle have rapidly increasing. Especially, as increasing development of environmetal-friendly vehicle as like to electric vehicle (EV) and hydrogen fuel cell vehicle, we expect to increase automotive electronics in cars. The restriction of End-of-Life Vehicles (ELV) began in January 2016 [1]. Due to the ELV banning, Pb-free solder must use in automotive electronics. Excavator electronics which is sorted to automotive electronics is using various electronics, and its proportion is continously increasing [2]. Because excavator is operating in harsh environment ; i.e. high and low temperatrue, high humidity, high vibration, the use of Pb-free solder in excavator demand to high reliability and quantititive evalutation of degradation characteristic of solder joints.

Reliability test method for lead free solder joint is generally used to thermal shock test, thermal cycling test, drop test and combined vibration test, etc [3-5]. Pb-free electronics are normally evalutated the degradation rate and its reliability based on measuring bonding strength and observing microstructrue of solder joints of diverse elecronic components in test vehicls. A lots of same components are soldered on the same test vehicle board. Fo example, when we test bonding strength, we usually use ten samples in the same board and different mounted location. Ten samples are measured bonding strength and calculate the mean value except the maximum and minimum values, and this mean value is regrad to the degree of solder joint degradation. Although a kind and the size are the same in the board, the strength deviation with the mounted location in the board always existed.

This study used vehicle electronic control unit (VECU) module which was mounted at cabin room of excavator. VECU module is important electronics for acting on engine rotation and fuel injection control, communication between systems and failure self-diagnosis. VECU module was soldered with Pb-free Sn-3.0Ag-0.5Cu solder. We compared the degradation rate of shear strength of solder joint with thermal cycling number and mounted location of chip resistors and chip capacitors. To analyze the root cause of deviation of shear strength degradation, we devided to four area of the VECU board with mounted components density, and then compared the temperature deviation with mounted components density. Based on these results, we analyzed the cause of the deviation of bonding strength with mounted components density during thermal shock condtion.

EXPERIMENTAL PROCEDURE

Vehicle Electronic Control Unit (VECU) Module

110 elelctronic components of Tr, FET, Diode, conntector, IC package, chip resistor and capacitor etc are soldered on a VECU board. 54 chip resistors and 29 chip capacitors were mounted on the board, and 1608 chips were the most used in a VECU module. Thus, this study compared to the solder joint degrdation using by the most mounted chip resistors and capacitors.

Solder Alloy, Printed Circuit Board and Reflow Soldering

Sn-3.0Ag-0.5Cu (Japan, Tamura Co., TLF-204-105S-3) solder alloy was used for reflow soldering of VECU module. Rosin Mild Activated Flux (Korea, Bumjin Material Co., FLUX DN-320 GHS) was utilized. Printed cuircuit board (PCB) was used FR-4 high temprature glass transition (Tg) material with 1.6 mm thickness, 6 layers, Cu 1oz [9]. Surface Finish of PCB was 25 ㎛ copper and electroless nickel immersion gold(ENIG, Ni=3 ㎛, Au=0.05 ㎛). VECU module was assembed by reflow soldering process. The reflow profile was 5 ℃/sec ramp rate, 150-200℃ peheating for 58 sec and 245 ℃ peak temperature with nitrogen gas purge.

Distinguished Area of VECU Module with Mounted Component Density

The photograph of VECU module is shown in Figure 1, which indicated four Areas and two Groups with mounted components density. In particular, the components density were divied into two main Groups. Group 1 contained Area 1 and 2, and Group 2 is Area 3 and 4 as shown in Figure 1. The components density was calculated as the raito of the area in which components were mounted compared to the area of the board. Also, an average density of fornt and back sides was used for the representitive components density. Componets density of Area 1 and 2 (Group 1) was 31.5%-39.4% and, Area 3 and 4 (Group 2) was was19.1%-19.9%. Componets density of Group 1 was near 20% higher than that of Group 2.

Table 1. Surface mounted components with areas classification

Measured Position	*Mounted Electronic Components*
Area 1	R5025, C3216
Area 2	Inductor, R6432(Back)
Area 3	R3216, Al-cap, R2012(Back)
Area 4	R1608, C2012

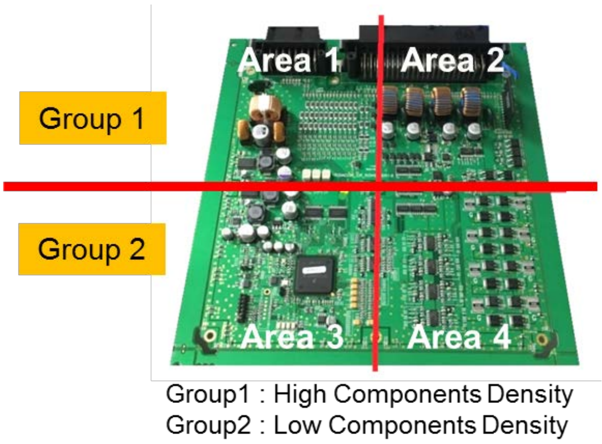

Figure 1. Photograph of classification of areas and groups on the VECU module with mounted components density

Table 2. Mounted Components Density with Area & Group of VECU Module

Measured Position	*Front Side Density (%)*	*Back Side Density (%)*	*Mean Density (%)*
Area 1	47.9	15.1	31.5
Area 2	60.8	18.0	39.4
Area 3	29.2	10.5	19.9
Area 4	25.8	12.4	19.1

Thermal Shock Test Condition and Board Temperature Measurement

To evaluate the solder joint degradation of VECU module, thermal shock test (Excal 120 CT, Climats Co., France) was conducted for 1500 cycles. Test condition was -40 ~ +125 ℃, 10min dwell at each temperature for 1500 cycles. Figure 2 was photograph of equipment set-up for thermal shock test and Figure 3 was a real temperature profile measured temperature from the VECU board during thermal shock test. We also measured shear strength of solder joint with a kind of components and mounted location before/after the thermal shock test. Shear strength was tested by bonding test machine (Dage 4000, Nordson Co., USA). To analyze intermetallic compound (IMC) of solder joint with test time, cross-sectional analysis was conducted, and the thickness and chemical compisition of IMC were analyzed using by SEM and EDS.

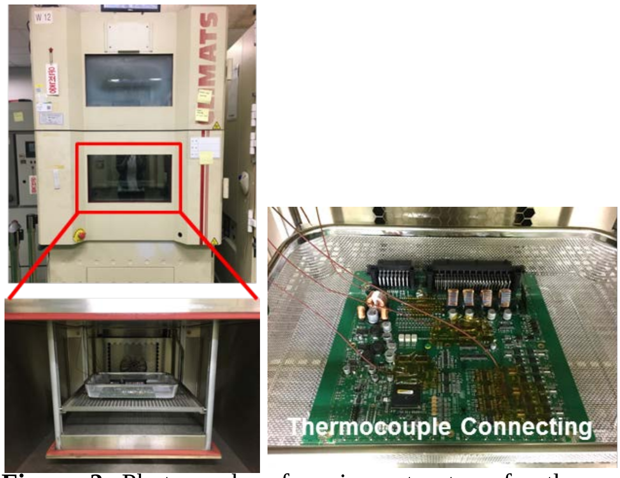

Figure 2. Photographs of equipment set-up for thermal shock test

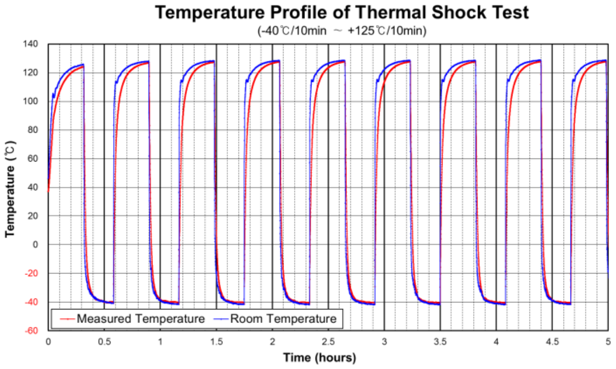

Figure 3. Temperature profile of thermal shock test of VECU modules

Heat Absorption & Desorption Property Measurement of VECU Module

To compare heating and cooling behavior of VECU module during thermal shock test, we measured it using by infrared (IR) cammera (Thermovision, Flir Co., A20, USA) as shown in Figure 4. VECU module kept at 125℃, 30 min and then take it out from chamber and leaved it alone in the atmosphere with observing surface temperature variation of the VECU. Simultaneously, we have measured the board temperature using by four thermocouples which were mounted on the board surface with components density areas.

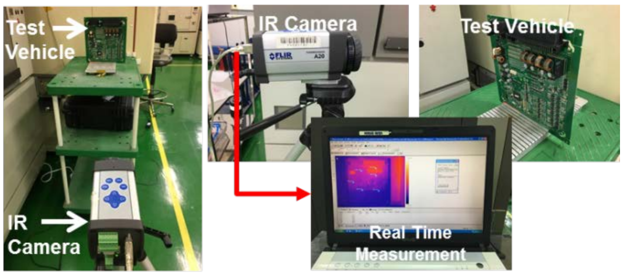

Figure 4. Photographs of *in-situ* temperature monitoring of VECU module using by thermal video system

RESULTS AND DISCUSSION

Difference of Board Temperature and Dwell Time with Components Density during Thermal Shock Cycles

In-situ monitered board temperatue with mounted components density from 4 region of VECU module was shown in Figure 5. In case of heating temperaure from low to high, real temperature deviation between room temperature of chamber and measured temperature on the VECU module with component density during thermal shock cycles was very small, and real dwell time in high temperature range was 8.4-9.0 min. Otherwise, in case of cooling from high to low temperaure, the cooling speed varied with mountinn components density.

The average dwell time changed at low temperatures as the temperature decreased slowly, resulting in a deviation of the average 2 minutes dwell time of 4.0-6.5 minutes per cycle. For Group 1 regions, the actual dwell time of 10 minutes at high temperatures and low temperatures was 506-542 seconds and 240-246 seconds, respectively. Otherwise, the actual dwell time of of Group 2 was 565-532 and 384-388 seconds in high and low tempeerautre, respectively. Base on this results, we have known that maximum 148 seconds (2.5 min) per cycle at low temperature range with mounted components density existed. As these variations in dwell time at low temperatures accumulated continuously for 1,500 cycles, we could suppose that the bonding strength degradation characteristics of solder joints presented to differ depending on the components density even though the same kind of electronic components.

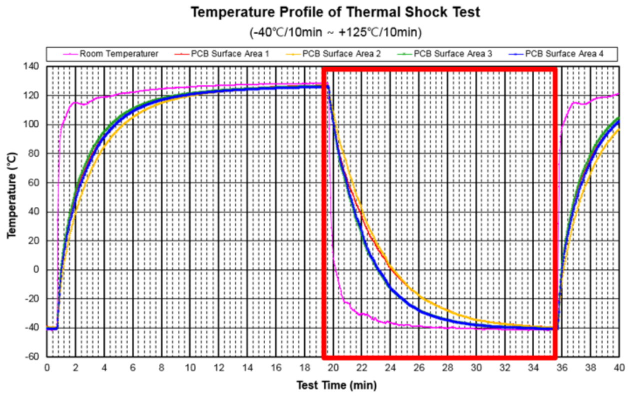

Figure 5. Real temperature deviation between room temperature of chamber and measured temperature on the VECU module with component density during thermal shock cycles

Figure 6(a) shows the temperature deviation by board location in more detail during cooling down from +125℃ to -40℃. We found that the temperatures in Areas 1 and 2 cooled slowly compared to those in areas in Areas 3 and 4. Figure 6(b), on the other hand, is the result of temperature measurement when it was heated from - 40 ℃ to 125 ℃. In this case, the temperature deviation occurred within 0.6 ℃ depending on the mounted components density, indicating that the difference was very small.

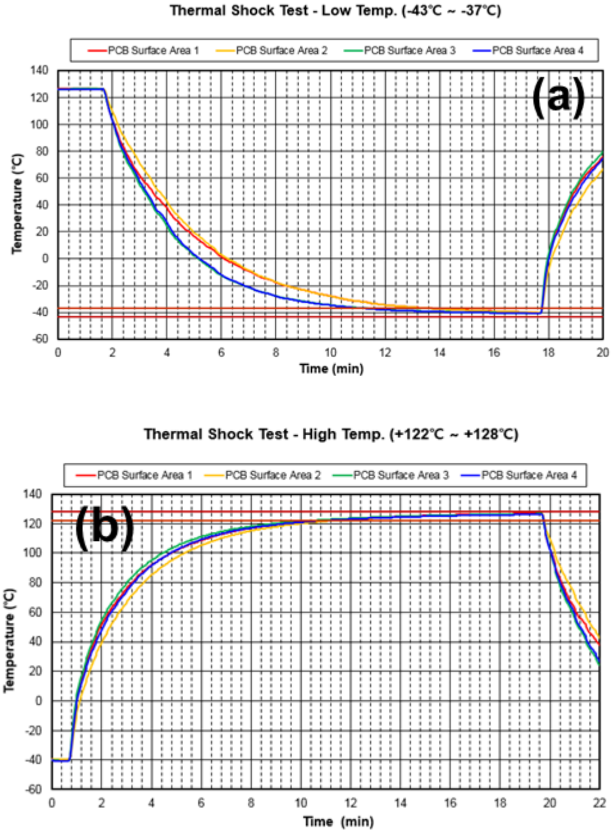

Figure 6. Temperature deviation near the (a) low and (b) high temperature range during cooling down and heating up with component density of VECU module

Heat Absorption & Desorption Measurement Results of VECU Module

To investigate whether the actual heating and cooling rate of the VECU module are different during heating and cooling, infrared (IR) cameras was used to measure the temperature of the board as shown in Figure 7. The VECU module was taken out at 125 ℃ chamber and leave in at room temperature, and the temperature of the board with cooled down was measured in real time for 15 minutes, simultaneously. From this test, when the VECU module cooled, we found that the board temperature cooled more slowly than in areas with a high mounted components density. Otherwise, when the module took out from -40 ℃ chamber, the temperature deviation between high and low components density areas was nearly simmillar. These results are consistent with temperature measurements on board using by thermocouple during thermal shock test. Consequently, the temperature of a high components density area increased well during the heating range from low to high temperature. Because it took more time to emit all the heat of the each components, the cooling speed was very slow.

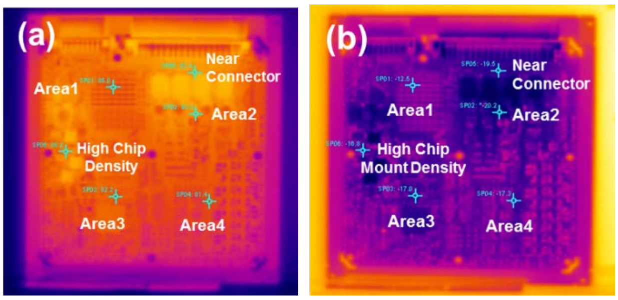

Figure 7. Photographs of *in-situ* temperature measurement result of VECU module using by thermal video system. (a) from 125℃ to 30℃ and (b) from -40℃ to 30℃

Shear Strength Degradation of Sn-3.0Ag-0.5Cu Solder Joint with Thermal Shock Cycles and Components Density

Figure 8 was the measurement results of shear strength of SAC305 solder joint with mounted position and component size after 1500 thermal shock cycles. The larger the volume of components showed the greater the shear strength degradation rate. In addition, the degradation rate of the joint strength after 1500 cycles compared to the initial joint strength of the R3216 parts, the shear strength degradation rate of the R3216 mounted in Area 2 decreased by -43 %, while that of Area 3 showed -35 %, which was decreased more by 10%. Also, it was found that the shear strength degradation of smaller parts in at least R3216 size was around 30 %, while that of larger parts such as 5025 and 6432 showed a decrease of 70 % or more in solder joint. Due to the dwell time deviation during thermal shock test, the Group 1 area which was a high components density experienced a more long time at a high temperature range. Consequently, the degradation rate of Group 1 (a high components density) area showed a faster than that of Group 2 (a small components density).

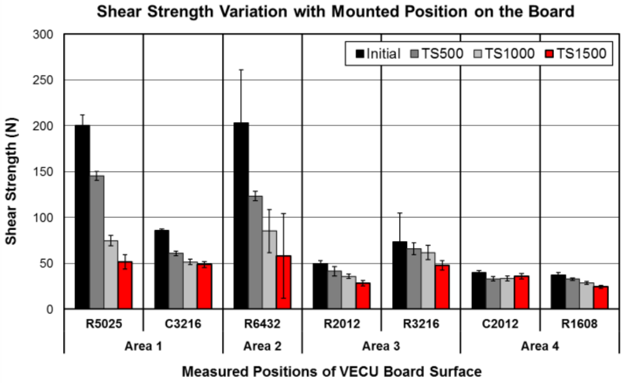

Figure 8. Shear strength variation of Sn-3.0Ag-0.5Cu solder joint with mounted position and component size after 1500 thermal shock cycles

Microstructure of Sn-3.0Ag-0.5Cu Solder Joint with Thermal Shock Cycles and Components Density

The cross-sectional SEM micrographs of chip resistors and capacitors with components density area and thermal shock cycles were shown in Figure 9. IMC layer thickness of Sn-3.0Ag-0.5Cu solder joint with components density after 1500 thermal shock cycles was shown in Figure 10. IMC thickness of Group 1 and group 2 of R3216 solder joints were 5.99 ㎛ and 4.30 ㎛, respectively. Due to its longer high temperature soak time in areas with a high component density, IMC thickness of the Group 1 was a thicker than that of the Group 2. Thus, in Group 1 area, IMC thickness was a thicker and shear strength degradation was a larger than the Group 2. Finally, during the thermal shock cycle, a high components density region within the same module could be extended a soak time at the high temperature range, which caused a thicker IMC growth and then, it was judged that the bonding strength of solder joints appeared to be smaller caused by the IMC growth [2,3,6-8].

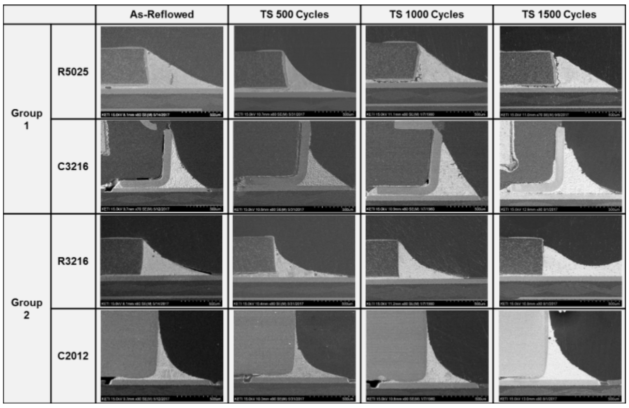

Figure 9. Cross-sectional SEM micrographs of chip resistors and capacitors with components density area and thermal shock cycles

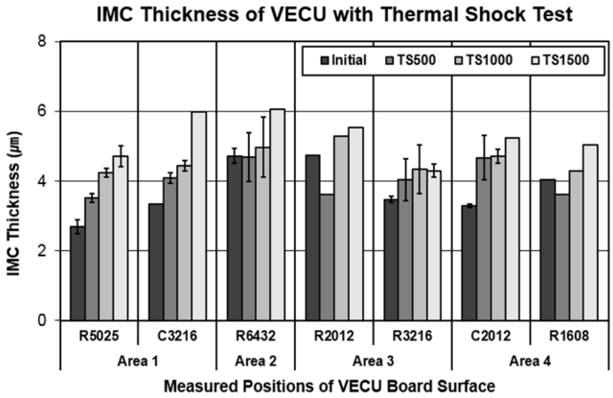

Figure 10. Intermetallic compound layer thickness of Sn-3.0Ag-0.5Cu solder joint with components density after 1500 thermal shock cycles

The traditional crack propagation mode under thermal shock condition was shown in Figure 11. The initial crack generated at the top side edge and under the termination edge of the solder joints and propagated into the solder joint interfaces. This crack represented the traditional fatigue crack shape. Based on the crack propagation mode, we could supposed that the crack caused by thermos-mechanical fatigue crack under the thermal shock condition [3,4,8-15]. When the solder joint exposed in thermal shock condition, the crack shape showed the traditional fatigue crack shape, which generated at the stress intensified area and propagated along the IMC interface of solder joint. $(Ni,Cu)_3Sn_4$ IMC was formed at between the chip termination and solder, and Ag_3Sn IMC was formed at the solder matrix. These IMCs grew thicker and larger with test time, which reason leaded to the solder joint degradation.

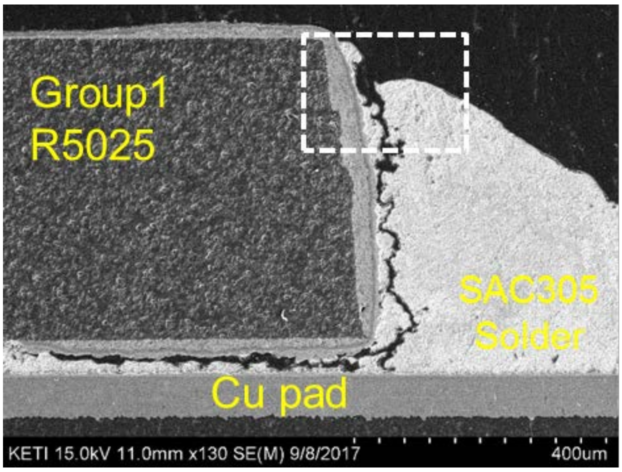

Figure 11. Cross-sectional SEM image of 5025 chip resistor solder joint mounted on Group 1 area of VECU wiring board after 1500 thermal shock cycles

CONCLUSIONS

We investigated the shear strength degradation of the SAC305 solder joints with mounted components density in the same board, and finally obtained the followed results.

We confirmed the deviation of absorption and desorption capability with mounted components density in printed wiring board. Due to the cooling rate deviation with components density, the heat desorption rate of a high components density region was very slow than that of low density area, and a large volume component showed a slow heat desorption rate. Therefore, in the region of high components density, shear strength degradation rate and IMC thickness of solder joints of high components density were larger and thicker than that of small density area due to insufficient time for recovery of heat stress. Consequently, the degradation rate of Group 1 (a high components density) area showed a faster than that of Group 2 (a small components density). During the thermal shock cycle, a high components density area within the same module could be extended a soak time at the high temperature range, which caused a thicker IMC growth and finally, these reason leaded that the bonding strength of solder joints showed to be smaller caused by intermetallic compound growth.

$(Ni,Cu)_3Sn_4$ and Ag_3Sn IMCs were formed at the solder joint interfaces and the solder matrix, respectively. The initial crack generated at the edge of the solder joint and propagated along the IMC interface of solder joint. To improve the solder joints reliability is necessary to consider the component size and mounted components density in the electrical board design.

REFERENCES

[1] European Union Council, COMMISSION DIRECTIVE (EU) 2017/2096 of 15 November 2017, Amending Annex II to Directive 2000/53/EC of the European Parliament and of the Council on end-of life vehicles, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017L2096, Accessed 17 July 2018.

[2] W.S. Hong, A.Y. Kim, Shear Strength Degradation of Pb-Free Solder Joint with Mounted Location in Automobile, Materials Transactions, Vol.56, No.7, 2015 pp. 1002.

[3] W.S. Hong, C. Oh, Thermal Shock Reliability of Low Ag Composition Sn-0.3Ag-0.7Cu and Near Eutectic Sn-3.0Ag-0.5Cu Pb-free Solder Joints, J. Kor. Inst. Met. & Mater., Vol.47, No.12, September 2009, pp.842.

[4] C. Oh, N. Park, W.S. Hong, Solder Joints Fatigue Life of BGA Package with OSP and ENIG Surface Finish, J. Kor. Inst. Met. & Mater., Vol.46, No.2, 2008, pp.80.

[5]. T.-K. Lee, B. Zhou, T. Biler, C.-F. Tseng, J.-G. Duh, The Role of Pd in Sn-Ag-Cu Solder Interconnect Mechanical Shock Performance, J. Electron. Mater., Vol.42, No.2, 2013, pp.215.

[6] W.S. Hong, W.S. Kim, N.C. Park and K.-B. Kim, Activation Energy for Intermetallic Compound Formation of Sn-40Pb/Cu and Sn-3.0Ag-0.5Cu/Cu Solder Joints, Journal of KWJS, Vol. 25, No. 2, April 2007, pp.82.

[7] I. Y. Lee, C. B. Lee, S. B. Jung, C. C. Shur, Growth Kinetics of Intermetallic Compound on Sn-3.5Ag/Cu, Ni Pad Solder Joint with Isothermal Aging, Journal of KWS, Vol.20, No.1, 2002, pp.97

[8] W.S. Hong, W.S. Kim, B.S. Song, and K.-B. Kim, Thermal Shock Cycles Optimization of Sn-3.0 Ag-0.5 Cu/OSP Solder Joint with Bonding Strength Variation for Electronic Components, Kor. J. Mater. Res., Vol.17, No.3, 2007, pp.152.

[9] IPC Standard:IPC-SM-782A, Surface Mount Designed Land Pattern Standard, Illinois, 1993.

[10] T.-K. Lee, W. Xie, Effect of Board Thickness on Sn-Ag-Cu Joint Interconnect Mechanical Shock Performance, Journal of Electronic Materials, Vol.43, Issue 12, December 2014, pp.4522.

[11] T.-K. Lee, B. Zhou, T. Bieler, K.-C. Liu, Impact of Microstructure Evolution and Isothermal Aging on Sn-Ag-Cu Solder Interconnect Board-Level High-G Mechanical Shock Performance and Crack Propagation, Journal of Electronic Materials, Vol.41, Issue 2, February 2012, pp.273.

[12] P. Kumar, Z. Huang, I. Dutta, R. Sidhu, M. Renavikar, R. Mahajan, Fracture of Sn-Ag-Cu Solder Joints on Cu Substrates. II: Fracture Mechanism Map, Journal of Electronic Materials, Vol.41, Issue 2, February 2012, pp.412.

[13] W.S. Hong, C. Oh, M.-S. Kim, Y.W. Lee, H.J. Kim, S.J. Hong, J.T. Moon, Al and Si Alloying Effect on Solder Joint Reliability in Sn-0.5Cu for Automotive Electronics, Journal of Electronic Materials, Vol.45, Issue 12, December 2016, pp.6150.

[14] H. Schoeller, G. Park, Isothermal Fatigue of High Temperature Solder Joints, SMTA Journal, Vol.30, Issue 2, 2017, pp.28.

[15] C. Zhao, C. Shen, Z. Hai, M.M. Basit, J. Zhang, M.J. Bozack, J.L. Evans, and J.C. Schuling, Long Term Aging Effects on the Reliability of Lead Free Solder Joints in Ball Grid Array Packages with Various Pitch Size and Ball Arrangements, SMTA Journal, Vol.29, Issue 2, 2016, pp.37