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A Study on the Effect of Different Interconnection Materials (Wire and Bond Pad) on Ball Bond Strength after Temperature Cycle Stress

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Abstract –Interconnection material is a important element in the industry. This study is investigate the effect of different interconnection materials on ball bond strength and study the effect of temperature cycling stress test on the ball bond strength. The literature review is based on comprehensive literature review from previous study. The strength on different interconnection materials of wire (gold and aluminum) and bond pad (copper and aluminum) after temperature cycle is investigated by using DMAIC methodology. The study is started with the reliability test with various Temperature Cycle (TC) stress and Failure Analysis testing was carried out to collect the wire pull strength value and ball shear strength value of different device.

Keyword: Wire pull, Ball shear, Temperature Cycle (TC), DMAIC methodology

I. INTRODUCTION

Due to the expanding use of electronics components in field of automotive and aerospace application, increased product lifetime and good reliability are needed to fulfill the customer's expectations on product quality. In particular, wire bond degradation is one of the major failure mechanisms that are affecting the product lifetime and reliability requirements typically at high temperatures.

The reliability of wire bonds is affected by wire diameter, loop height, material purity and manufacturing processes. By referring to Ghaffarin (n.d.)[13] reliability must be an integral part of development and implementation, it is no longer an "after-the-fact" concept. [21] defined reliability as the "probability that a device will perform its required function in stated conditions for a specific of time". Therefore, the reliability specifications of power electronic in sectors such as aerospace and automotive are different due to differences in the external environment and expected lifetimes of the product in these sectors.

The most widely used methods for controlling the reliability of the bonding process and estimating the lifetime of bond wire connections are temperature cycling experiments and with the combination of bond wire pull tests. Temperature cycling tests are used for accelerated fatigue testing with very high temperature swings, normally 150 K and more.

The purpose of this study is to investigate the strength on different materials of wire and bond pad after temperature cycle stress. The differences between gold wire and copper wire, aluminum pad and copper pad perform during pull and shear tests will also be investigated. The reliability test used in this study is Temperature Cycling Stress.

II. LITERATURE REVIEW

There are two section presented in literature review:

A. Wire Bonding

Wire bonding has been the predominant interconnect technology for more than 40 years and holding more than 85% of the market share [2] Wire bonding is an important technology used in the microelectronic packaging industry and makes electrical connections for microelectronic packaging. Wire bond carries power and signal between Integrated Circuit (IC) and lead frame [32]. It is generally considered as the most cost effective and flexible technology and is used to assembly the vast majority of semiconductor device [7]. Wire bonding is an electrical interconnection technique using thin wire and a combination of heat, pressure and ultrasonic energy. The common wire diameters range from 15 to 25µm and thicker on power devices. There are basically two forms of wire bonding technique, which are wedge bond and the ball bond [8].

B. Comparison between Copper Wire and Gold Wire

Most semiconductors devices have utilized gold wire in wire bonding process [20]. Due to the price of gold wire has greatly increased, it has led to increased interest in replacing gold wire with copper wire in existing wire bonded packages and implementing copper wire as a standard in new packages, which can lead to significant cost savings due to lower raw material cost [3][11]. Moreover, copper is not subject to sudden price fluctuations in the market [6].

Copper wires have better thermal and electrical properties than gold wires [29][7]. Copper has about 25 per cent more conductive than gold, copper wire dissipate heat within the package faster and more efficiently than gold wire and increased power rating. Higher electrical conductivity leads to less-heat generation and a higher speed [28][26].

Compared with the Au-Al system, there is very little void formation in the Cu-Al system [14] Cu-Al intermetallic compound (IMC) growth rate is significantly less than the Au-Al intermetallic growth rate [18]. This is because an atom of copper has a large size mislift with aluminum and lower electronegativity compared to an atom of aluminum [29]. The growth rate is more than an order of magnitude slower than gold. At time zero, the wire pull and ball shear strength of copper wires are considerable higher than for corresponding gold wires although the Cu-Al intermetallic compounds are extremely thin [2]. The thin Cu-Al IMC at the bonding interface results in better bond strength and smaller electrical resistance [31].

The Au-Al IMC grows laterally and vertically at the interface at temperature 150°C [16]. The initial intermetallic phase can thicken due to thermally activated reactive diffusion consuming the entire aluminum pad metal in less than 20 hours [4]. During bonding process, the region that is no IMC formed and no development of IMC in vertical direction may produce an unbalance effect on atomic diffusion along grain boundary in spatial content. When a great many of vacancy concentrations occurs at this point, this inclines to become a Kirkendall void [16].

Kirkendall voiding will begin to occur once the aluminum has been consumed under the ball bond. Kirkendall void formation at the interface between the Al pad and the Au-Al intermetallic is a typical lifetime wear out mechanism for a gold wire bond [12]. From the packaging quality point of view, Kirkendall voids may accelerate deterioration of the bonding force and even ball lift from pad. In practice, the generation and growth of the Kirdendall voids can be improved by achieving a good and even Au-Al IMC coverage on aluminum bond pad in as-bonded samples [16].

According to the study of Onuki (1987) [23], he reported that the amount of intermetallic present will have an effect on the bond strength. The bond strength of the Cu-Al bond is above 50% even after 200 hours of aging at 200°C while Au-Al bond is below 50% of the original value. The bond strength of copper and gold ball bonds is similar below 180°C.

Increased growth of IMCs can also result in greater brittleness and contact resistance increase, leading to more heat generation in service. This, in turn, accelerates the growth of IMCs, finally causing failure of such bonds [29].

Although copper wire has many advantages over gold wire, but it also has some disadvantages. Copper tends to undergo oxidation at relatively lower temperatures, and therefore copper wire bonders must have additional tools to prevent copper oxidation [14]. Oxidation of copper wire leads to poor bondability for stitch bonds [17], which can result in increased non-sticking rates. The progressive of the wire oxidation will also cause a significant reduction of wedge bond strength [19].

In addition, copper wires have much higher hardness and stiffness than gold wires. Hence, copper wire bonding needs more ultrasonic energy and higher bonding force, which can damage the Si substrate, form die cratering [14] and induce cracking and peeling of the bonding pad [18]. By referring to Khoury et. al. (n.d.), cratering in copper ball bonding has been reported when bond forces were in the range of 80 to 150gf at ultrasonic power levels of 20mW. As-drawn copper wire possesses higher strength and hardness, but its lower ductility reduces the reliability of bonding. The lower strength of the annealed wire results in breakage [15].

The pads occasionally lifted, but this was not detrimental because the pull strength values were not smaller than the neck break values. Mechanical properties of the Copper bonds were superior to those of gold bonds [33]. A copper ball is too strong (compared to a gold ball) to be sheared in half after it work-hardens during ball bonding. The Cu-Al interface is the weakest link in the system, and therefore the ball lifts during the shear test [11].

C. Temperature Cycle (TC)

Among the many environmental accelerated testing methodologies for assessing reliability of electronic systems, temperature cycling is the most commonly used for the characterization of devices as well as interconnections. The military and commercial ranges represent the two extremes from the many predefined temperature cycling profiles. Previously, NASA also had a preset specific thermal cycling requirement. Although a number of Military Standards were obsolete, they are still used for benchmark testing. For example, within MIL-STD-883, there are three levels of accelerated cycling temperatures, which are:

i) Condition A, -55°/85°C
ii) Condition B, -55°/125°C
iii) Condition C, -65°/150°C

Temperature cycle testing is used as a method of determining the device’s resistance to the high and low temperature extremes. This test exposes the device packaging to mechanical fatigue induced by thermal expansion. [24] stated that the purpose of thermal cycling is to determine the electrical performance of wire bond interconnect to the temperatures alternatively changed.

While, according to the JEDEC Standard (2009) as cited in [31], the temperature cycling test is “conducted to determine the ability of components and solder interconnects to withstand mechanical stresses induced by alternating high and low temperature extremes. Permanent changes in electrical and/or physical characteristics can result from these mechanical stresses.”

D. DMAIC Methodology

A scientific approach is needed in order to solve and improve the problem solving close to its source [25]. Thus, DMAIC methodology is evolved from W. Edwards Deming's version of the plan, do, check, act (PDCA) cycle and is also known as the Shewhart Wheel after its inventor, Walter Shewhart [27]. DMAIC methodology provides the framework to improve existing processes in a systematic way [22]. DMAIC methodology is not only useful for problem solving; it also works well as a checklist for doing any other type of project [10]. DMAIC methodology also provides the structure, discipline, and logical progression for achieving breakthrough improvements [5]. This methodology involves a cycle that is comprised of five phases: "Define", "Measure", "Analyse", "Improve", and "Control" (DMAIC) [1]. In each phase, established quality techniques and quality tools are used to generate specific results for that phase [9].

III. METHODOLOGY

A. Define Phase

In define phase, the problem is identified and the experiment is planned well. The experiment is started with the reliability stress with various Temperature Cycles. Then, Failure Analysis process is performed to analyze the quality of the device. It is started with non-destructive test, which is Scanning Acoustic Microscopy (SAM) to access the internal package integrity. Next, follow by the destructive test, which is performed to obtain the pull and shear test's result.

B. Planning and Design of Experiment

In this experiment, four types of device are selected. There are two kinds of parameter, which are type of wire and material of bond pad with various temperatures cycling stress test.

(A) Type of Wire

Table 3.1: Different of wire.

	Group A	**Group B**
Wire	Gold (Au)	Copper (Cu)
Bond Pad	AlSiCu	AlSiCu
Wire Size	50μm	50μm
Stress	TC	TC

(B) Material of Bond Pad

Table 3.2: Different of bond pad.

	Group C	**Group D**
Wire	Copper (Cu)	Copper (Cu)
Bond Pad	Copper (Cu)	AlSiCu
Wire Size	30μm	30μm
Stress	TC	TC

C. Measure Phase

Measure phase is used to plan how to collect the data for the analysis of the problem. It also used to determine what level of sampling is needed to represent the problem condition and determine the selection of measuring instrument By followed this methodology design stage, the project can be carried out with smooth flow and the time spending in the process can be reduce.

Table 3.3: Sampling plans

Group	Sampling per Experimental	
	Units	Wires per unit
A	3	9
B	3	16
C	3	26
D	3	10

D. Analyze Phase

Analyze phase of DMAIC methodology is used to analyze the data obtained from the pull test and shear test. The data is analyzed by using graphical analysis such as control chart.

E. Improve Phase

Generating solution ideas is the first step of the Improve phase. Some tasks such as review of the process and verification of root cause, brainstorming of solution items and transforming of idea into solution are carried out to arrive at solution.

F. Control Phase

In control phase, it is important to make sure that the improvement can be sustained. A standard framework when carried out this study can be developed and documented.

IV. RESULT AND DISCUSSION

A. Analyze Phase

In analyze phase, the bond strength of different interconnection materials after temperature cycle stress is analyze in two forms: different wire type with constant bond pad and different bond pad system with constant wire type.

Pull and Shear Strength with Different Wire Material (Gold and Copper)

Moving towards next level of major cost saving in packages, conversion form gold wire to copper wire became necessary action in semiconductor field. In order to have a successful conversion of wire material, a comparison between gold wire and copper wire under constant aluminum bond pad has been carried out. Wire pull and ball shear test were performed on the device after temperature cycle (TC) stress. Figure 4.1 shows the graph of wire pull strength versus temperature cycle stress for constant bond pad.

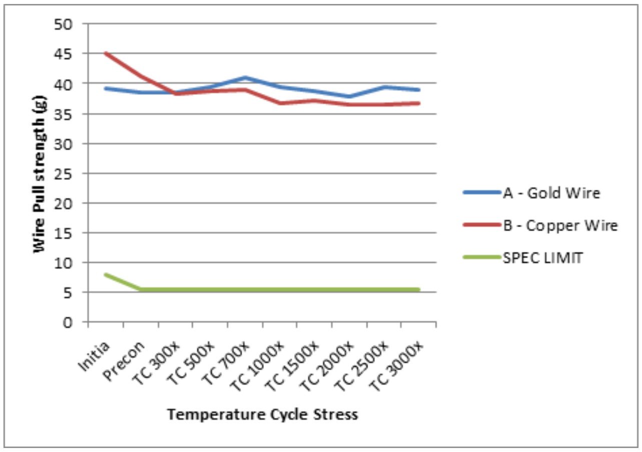

Figure 4.1: Wire pull strength versus Temperature Cycle (TC) stress for constant pad.

As been seen, the graph shows that the strength of copper wire decrease with TC stress. While, the strength of the gold wire remain constant with respect to the TC stress carried out at the device. In initial stage (before stress), copper wire is more hardness than gold wire, thus, the strength of copper wire is higher than gold wire and is gradually decreased along the stress. This has been proved by Hung et. al. (2006), which state that the hardness properties of copper will lead it to high pull and shear value.

e strength values with respect to the TC stress of gold wire are in the average range of 38 – 41g and strength values of copper wire are average 36 – 45g. As the stress increased to TC 300x, there is a intersect point observed between the gold wire and copper wire. The strength value of gold wire is to be gradually higher than the copper wire after TC 300x. The slightly higher pull value of gold wire is basically due to coefficient thermal expansion (CTE) different between gold wire and copper wire. The CTE of gold is 14.2 um/m K, copper is 16.5 um/m K, CTE of mould compound for Group A is 11 um/m K and CTE of mould compound for Group B is 12 um/m K. As a result of the different between the CTE values between two interface materials, CTE different of mould compound with respect to copper wire (4.5um/m K) degrade the pull result more than gold wire (3.2 um/m K). Hence, it can be concluded that the higher the different of CTE between two interfaces, the higher the possibility the strength of the ball bond will be degraded. When performing wire pull test for both gold wire and copper wire, the wire breaks at the soft ball necks region and the ball is still remains firmly attached to the pad.

The trend of ball shear strength graph almost similar to the trend of wire pull strength graph which is shown in Figure 4.2. Due to the mismatch of CTE between the mould compound and wire, the shear strength of gold wire (average 154 – 206g) and copper wire (average 149 – 215g) gradually decreased with TC stress. Same with the wire pull strength, the ball shear strength of copper wire is higher than gold wire from initial stage to TC 300x due to its properties.

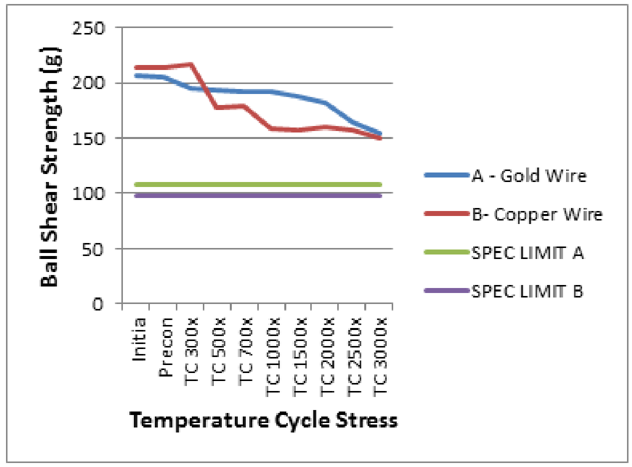

Figure 4.2: Ball shear strength versus Temperature Cycle (TC) stress for constant bond pad.

There is an IMC formation between gold wire and aluminum pad is observed from initial stage until TC 3000x. The initial intermetallic phase can thicken due to thermally activated reactive diffusion consuming the entire aluminum pad metal in less than 20 hours. While, there is no visible IMC grow in copper wire. Significantly, the Cu-Al IMC growth rate is less than the Au-Al IMC growth rate. Thus, after TC 300x, the shear value of gold wire become more dominant than copper wire (average 30g difference) and reach a match point where gold wire and copper wire’s value close to each at TC 2500x.

The diffusion of gold wire to aluminum pad is faster than copper wire to aluminum pad. This is because the atomic inter-diffusion rate in the Au-Al IMC is quiet active due to similar atomic radii and large difference in electeonegativity. The graph shown in Figure 4.3 describes the speed of the IMC growth with respect to the stress. The Au-Al IMC grows laterally and vertically at the interface along the TC stress. The graph indicate the higher the stress, the higher the IMC value. As the devices undergo stress, the IMC will significant growth until the aluminum fully consume. This have directly result the ball shear strength value between gold wire and copper wire become no significant different after TC 2500x.

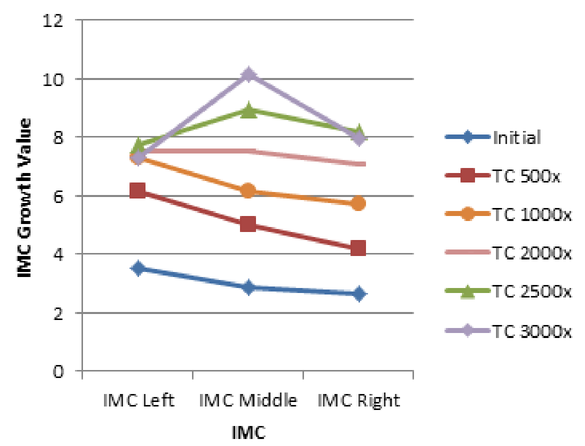

Figure 4.3: Graph of IMC Growth for Gold Wire.

Hypothesis testing has also been carried out to evaluate the mean of wire pull and ball shear strength for gold wire and copper wire at TC 3000x. The purpose of performing hypothesis testing is to support the experimental statement which states that the strength value of copper wire at TC 3000x is lower than gold wire. The testing is carried out by using Minitab software and the result for wire pull strength for both wires is shown in Figure 4.4 and Figure 4.5. While, the result for ball shear strength please refer to Appendix.

Two-Sample T-Test and CI: GA - TC 3000x, GB - TC 3000x

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Two-sample T for GA - TC 3000x vs GB - TC 3000x

               N   Mean  StDev  SE Mean
GA - TC 3000x  27  39.06   3.59     0.69
GB - TC 3000x  27  36.47   2.85     0.55


Difference = mu (GA - TC 3000x) - mu (GB - TC 3000x)
Estimate for difference:  2.595
95% CI for difference:  (0.822, 4.368)
T-Test of difference = 0 (vs not =): T-Value = 2.94  P-Value = 0.005  DF = 49
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Figure 4.4: Two-Sample T-Test for gold wire and copper wire at TC 3000x.

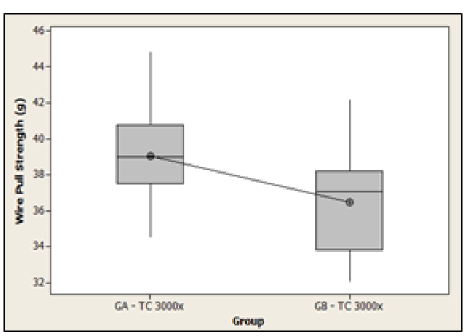

Figure 4.5: Boxplot of wire pull strength for gold wire and copper wire.

Null hypothesis: The sample mean is same.
Alternative hypothesis: The sample mean is not same.

From the result shown in Figure 4.4, it shows a sample of 27 wires was measured and the sample mean and standard deviation for gold wire are 39.06g and 3.59g respective. While, the sample mean for copper wire is 36.47g and standard deviation is 2.85g. The estimate for difference is 2.595 and the degree of freedom is 49. Besides that, the result shows that the null hypothesis different is zero and it does not include in the range of the 95% confidence interval difference. Then, it also shows that the t test value calculated for the hypothesis test is 2.94. Since that the p-value is less than 0.05, thus, the null hypothesis is rejected. It can be concluded that there is not enough sufficient evidence to prove that the true mean for both gold wire and copper wire are same. The result also same for the ball shear stress which the null hypothesis is rejected and concluded that the true mean for both wire are not same.

Pull and Shear Strength with Different Bond Pad (Copper and Aluminum)

In addition, the wire pull strength and ball shear strength for different bond pad is also investigated in this study. Figure 4.6 shows the graph of wire pull strength versus TC stress. The difference between bond pads does not affect the wire pull strength, which the strength value between both bond pad system (copper pad and aluminum pad) is not significant different (average 13 - 15g for both pad system) and it just have an average of 2g difference along the stress. The CTE of mould compound for Group C (copper pad) and Group D (aluminum pad) is same, which is 6.6 um/m K. Thus, the different of CTE between the interface (mould compound and wire) for both of the group are the same. As a result, as the stress increased, the strength value not fluctuated irrespective to the TC stress with different bond pad.

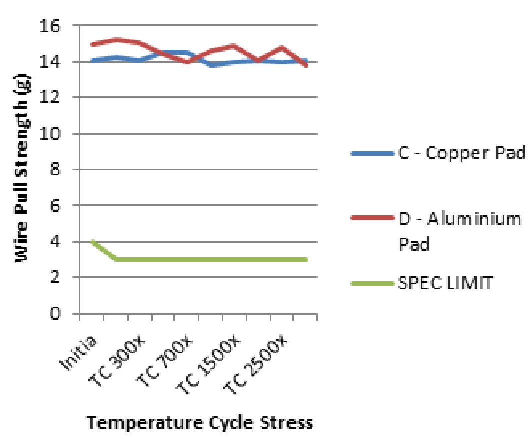

Figure 4.6: Wire pull strength versus Temperature Cycle (TC) stress for different bond pad.

As same with wire pull strength, the ball shear strength on different pad system has also no significant different after TC stress due to both systems have the same value of CTE. The ball shear strength graph is shown in Figure 4.7.

After performed cross section on the device, a formation of IMC between gold wire to aluminum pad can be observed under optical microscope. The strength value for Au-Cu system is slightly lower than Au-Al system due to the lightly formation of IMC in Au-Cu system. The IMC in Au-Cu system is invisible under optical microscope.

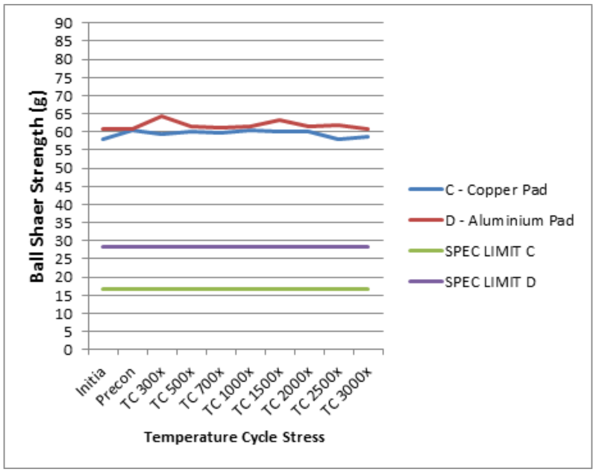

Figure 4.7: Ball shear strength versus Temperature Cycle (TC) stress for different bond pad.

Hypothesis testing has also been carried out to evaluate the mean of wire pull and ball shear strength for copper pad and aluminum pad at TC 3000x. The purpose of performing hypothesis testing for different bond pad system is to support the experimental statement which states that the strength value of for both of the bond pad system (copper and aluminum) at TC 3000x is not significant different. The testing is then carried out by using Minitab software and the result for wire pull strength for both bond pad system is shown in Figure 4.8 and Figure 4.9. While, the result for ball shear strength can refer to Appendix.

Two-Sample T-Test and CI: GC - TC 3000x, GD - TC 3000x

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Two-sample T for GC - TC 3000x vs GD - TC 3000x

              N   Mean  StDev  SE Mean
GC - TC 3000x 30  14.02  1.46    0.27
GD - TC 3000x 30  13.82  1.28    0.23


Difference = mu (GC - TC 3000x) - mu (GD - TC 3000x)
Estimate for difference:  0.193
95% CI for difference:  (-0.518, 0.905)
T-Test of difference = 0 (vs not =): T-Value = 0.54  P-Value = 0.588  DF = 57
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Figure 4.8: Two-Sample T-Test for copper pad and aluminum pad at TC 3000x.

From the result shown in Figure 4.8, it shows a sample of 30 wires was measured and the sample mean and standard deviation for copper pad are 14.02g and 1.46g respective. While, the sample mean for aluminum pad is 13.82g and standard deviation is 1.28g. The estimate for difference is 0.193 and the degree of freedom is 57. Besides that, the result shows that the null hypothesis different is zero and it is included in the range of the 95% confidence interval difference. Then, it also shows that the t test value calculated for the hypothesis test is 0.54. Since that the p-value is more than 0.05, thus, the null hypothesis is accepted. It can be concluded that there is sufficient evidence to prove that the true mean for both gold wire and copper wire are same. The result are also same for the ball shear stress which the null hypothesis is accepted due to it p-value (0.391) is more than 0.05 and can be concluded that the true mean for both wire are same.

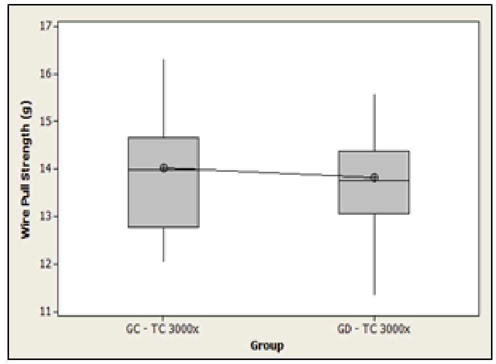

Figure 4.9: Boxplot for copper pad and aluminum pad at TC 3000x.

B. Improve Phase

After analyzing and understand the sources of variation, the Improve phase enables actions to reduce variation or solve the problem. In this study, the improvement that can be done is further the TC stress until the ball is lifted can be noticed. Further the TC stress until 4000 cycle on the devices enable the Cu IMC continuously growth. Besides that, investigate the relationship between the strength and the IMC growth of the copper devices can be performed. This action can determine how the reliability of the device after performing the stress. In addition, Cu IMC is no visible under optical microscope, hence, in order to ascertain the interface characteristic of Cu-Al bond, a cross-sectional SEM image and TEM image at higher resolution can be used to shows the growing rate of IMC particles that form between aluminum and copper.

C. Control Phase

Once the improvement is realized, the goal is to control the improved process and sustain the improvement. A control document such as Standard Operating Procedure (SOP) can be used to document the procedures that need to be followed by the user. A SOP is a set of written documents or instruction detailing all steps and activities of a process or procedure. All procedures used in any manufacturing process is essentially to be documented as to fulfill the requirement of ISO 9001, which is provide a quality product to customer. SOP should be written in a concise, step-by-step and easy to read format. The information presented should be simple and clearly which enable someone with limited experience with that procedure can successfully understand and reproduce the procedure when unsupervised. The use and development of SOP can minimizes variation and promotes quality through consistent implementation of a procedure or process. Since it provides detailed work instruction, thus, it minimizes the chance or opportunities for miscommunication. Besides that, SOP can also be valuable for reconstructing project activities when there are no other references are available. Due to confidential issues, the SOP of this study is not included in this paper.

V. CONCLUSION

As conclusion, for the device with constant bond pad, the wire pull strength and ball shear strength of copper wire performed better than gold wire in initial stage until TC 300x due to its hardness properties. The strength values with respect to the TC stress of gold wire are in the average range of 38 – 41g for wire pull and average 154 – 206g for ball shear; and wire pull strength values of copper wire are average 36 – 45g and ball shear are average 149 – 215g. The pull strength value is observed to be gradually decreased and lower than gold wire after TC 300x. The difference of the CTE value between gold wire and copper wire significantly affect the strength value, where the higher the different of CTE between two interfaces, the higher the possibility the strength of the bll bond will be degraded.

The diffusion of gold wire to aluminum pad is faster than copper wire to aluminum pad. Hence, the Cu-Al IMC growth rate is less than the Au-Al IMC growth rate. Thus, after TC 300x, the shear value of gold wire become more dominant than copper wire (average 30g difference) and reach a match point where gold wire and copper wire's value close to each at TC 2500x when aluminum is fully consume in the system.

For different bond pad, the wire pull and ball shear strength for both group (copper bond pad and aluminum bond pad) with the same value of CTE (6.6 um/m K for mould compound and gold wire is 14.2 um/m K) does not fluctuate with respect to TC stress. The strength value for Au-Cu system is slightly lower than Au-Al system due to the lightly formation of IMC in Au-Cu system.

From the experiment have been carried out, it is noticed that the gold wire performed better than copper wire in both of the pull and shear test. Thus, it can be concluded that the copper wire performed poorly in temperature cycling. Further study can extend the temperature cycle stress until 4000 cycle to check the ball condition during pull and shear test.

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