DEVISING VARIATION REDUCTION TECHNIQUES FROM STATISTICAL PROCESS CONTROL (SPC) SIGNALS TO ACHIEVE WIRE BOND PROCESSs STABILITY

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ABSTRACT

Bondability tests measure and evaluate the integrity of wire bonded connections; in particular, for ball shear tests, lateral load is applied on the ball bond to gauge the strength of its adhesion on the pad. The results of these bondability tests are recorded and monitored through statistical process control (SPC) charts which then provide small signals to assess the capability of the process which is ideally at a CpK of 1.67. However, only 81% of wire bond SPC charts are hitting the target CpK and the failing charts are mostly attributed to poorly performing ball shear charts. Using Lean Six Sigma approach and the Define-Measure-Analyze-Improve-Control (DMAIC) methodology, the sources of variation for each failing chart was identified, and with it, a corresponding solution was implemented. SPC Chart Limits Information System (CharLIS), an automated system that pulls out chart information regarding a specific lot through a statistical tool, was developed to reduce man-related variation and promote zero-decision among operators and technicians. Man- and method-related variations were addressed through standardization of ball shear methodology. Bond program optimization and standardization as well as increasing bond parameter X were also done to minimize recipe- and method-related variation. Furthermore, the feasibility of using shear per area charts to address measurement- and method-related variation was also explored. Implementation of these solutions and innovations led to 46% decrease in lifted ball defect rate and approximately US$47K savings per year is expected from the reduced manhours.

1. 0 INTRODUCTION

Wire bonding process involves forging electrical interconnections between the die and the leads using a combination of heat, force, and ultrasonic energy. In order to assess a wire bonder setup and the integrity of the bonds being formed, bondability tests are performed on sample bonded units.

The strength of ball adhesion is measured through the ball shear (BS) test wherein lateral load is applied to the sample and shears the bond from its surface[1]. Wire pull (WP) test is also performed to measure the bond strength as well as evaluate the failure mode at which the wire bond will break. This is done through application of an upward force under the wire sample and effectively pulling it away from the die[1]. Both tests will give readings in gram-force (gF) with higher readings signifying stronger bond strength and adhesion.

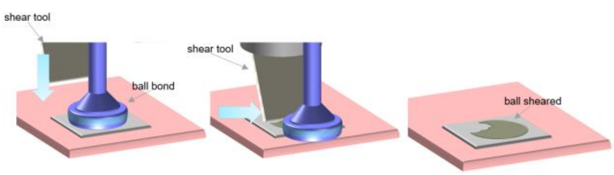


Fig. 1. Illustration of the ball shear process. Shear tool applies lateral load on the ball bond and gives a reading/measurement in gram-force (gF).

It is ideal to perform bondability tests for every wire bond setup to ensure that the combination of parameters would not lead to electrical fails and reliability risks. Monitoring the results of these tests across multiple setups through statistical process control (SPC) charts would therefore paint a picture of the wire bond process capability.

SPC charts make use of statistical methods that provide a feedback loop to compare the wire bonding process performance against set limits. Small signals from SPC calls for action to variations encountered. The process performance is measured through the process capability index (CpK), which is given by Equation (1).

$$CpK = \frac{(Mean - LSL)}{3\sigma} \qquad \textit{Equation 1}$$

where Mean is the average value, LSL is the lower specification limit and σ is the standard deviation.

Variation is inherent in any process and no two units produced would be exactly alike, but from Equation (1), minimizing variation is key to increasing the process capability index.

The process capability index (CpK) is a parameter that measures how well a process meets the specifications and the extent of variation it experiences relative to its limits[2]. For each SPC chart, the target CpK is at least 1.67 which indicates that the process is at five sigma, meaning it is excellent or capable. To assess whether the process is performing within the desired limits, it is imperative that all automotive SPC charts have a CpK of 1.67 or better.

However, only 81% of SPC charts are able to attain at least 1.67 CpK. These failing charts consist of ball shear charts for different device attributes and different device families. Failing ball shear chart entails that either the ball shear readings are too low (i.e. there is very little margin between the mean value and the lower spec limit) or the measurements are fluctuating (i.e. the range of values being read are too far apart from each other). Either way, a failing ball shear chart suggests poor ball bond integrity and lack of process robustness at wire bond. There is a multitude of factors that contribute to variations in ball shear measurement; the challenge lies in determining which one significantly impacts the process capability. Since the SPC charts in question also vary in wire type and diameter and in bond pad material and technology, there is no catch-all root cause and solution—rather the approach in analyzing the failing charts is universally applicable regardless of the device attributes.

The study highlights the utilization of Lean Six Sigma approach and 7QC tools to identify the sources of variation for each failing chart. Solutions to address the man-, machine-, material-, method- and measurement-related sources of variation are also presented, as well as the effectiveness of each in improving the process capability.

2.0 METHODOLOGY

The study deals with process improvement using small signals from SPC charts. Since SPC charts are essentially a collection of datapoints recorded over time and the main challenge being tackled is the reduction of variation in the wire bonding process, Lean Six Sigma was deemed to be the most fitting problem-solving approach to use.

2.1 Define Phase

During regular wire bond SPC reviews, several charts were noted to have consistently failing CpK. Overall, only 81% of the charts were meeting the passing CpK requirement of 1.67 versus the target attainment of 100%. These charts were clustered according to their common wire and bond pad attributes and were summarized in Table 1.

Table 1. Summary of Failing SPC Charts and their Corresponding Attributes

Chart	Wire Attribute	Bond Pad Material
Cu-BOAC	Copper (Cu)	BOAC
PC-Al	Palladium Coated Copper (PCC)	Aluminum
Au-Al	Gold (Au)	Aluminum

2.2 Measure Phase

Initially, the team mapped out and reviewed the current ball shear process and general setup buyoff process at wire bond. The detailed process mapping served as the main reference in listing down all factors contributing to the CpK and in establishing the baseline process.

2.2.1 Identification of Possible Root Causes

An Ishikawa or Fishbone Diagram was used to list down all possible factors that introduce variation during ball shear measurement. Additionally, the wire bonding process—particularly that of the 1st bond (wherein ball is bonded unto the pad)—was reviewed to track any source of ball adhesion inconsistencies during bonding. These factors were grouped as man-, machine-, material-, method-, measurement- and environment-related. A total of 18 factors were identified and are shown in Appendix A.

2.2.2 Control Chart Performance and Spider Chart Analysis

At least three (3) months data was pulled up for each failing control chart to characterize the baseline. The charts were screened for any out-of-control points both in the Xbar (top) chart and in the range (bottom) chart, which were consequently validated. The charts were then cleaned up to rid of any invalid datapoints recorded (such as incorrect inputs and human error) to eliminate noise in the dataset.

Spider charts were then utilized to get a pulse of the dataset—whether the poor CpK is simply due to poor chart centering which can be easily solved by limits recalculation, or if significant process variations are causing the CpK to drop (See *Fig. 2*). The charts of interest are those the remain to have a failing CpK even after centering has been performed. These charts were further broken down for analyses in the next phases.

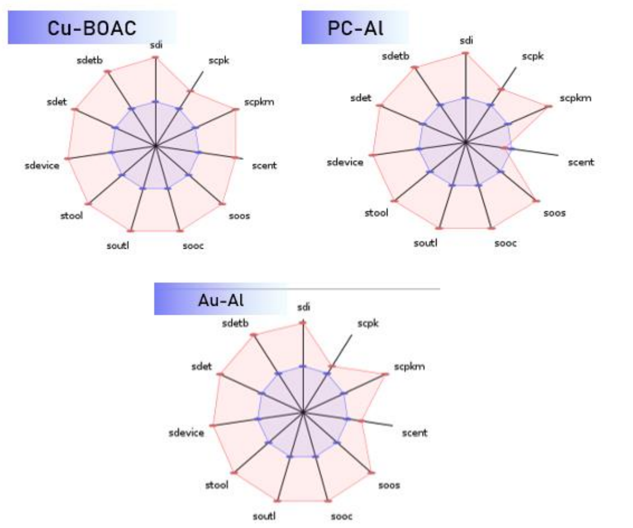


Fig. 2. Spider chart for Cu-BOAC, PC-Al, and Au-Al SPC charts.

2.3 Analyze Phase

Each failing chart was scrutinized against the identified list of possible root causes in 2.2.1 through validation tables. The verification method of each item usually involves checking for any commonality in the ball shear response for each factor. For the most part, this is accomplished by analyzing the available historical data in a statistical tool. However, for Chart Au-Al and Chart Cu-BOAC, experimental validations were also performed to gauge the effect on ball shear readings when certain bonding conditions are altered.

Table 2 summarizes the validation tests for each factor possibly contributing to failing CpK for Chart Cu-BOAC. From initial check on device commonality, better CpK was noted for devices having only small or single BOAC pads versus devices with combination of big and small BOAC pads. Additional validation was done to check the ball shear response on small pads versus big pads, however, no significant difference was observed (P-value > 0.05). Further review of the process and line interviews then revealed that there is no existing standard on how ball shear on BOAC devices should be performed.

Table 2. Validation Table for Chart Cu-BOAC

Cat.	Root Cause	Verification Method	Remarks
Man	Operator BS method	Check BS readings uploaded by different operators	Varying BS response among operators even for a single device
Machine	Platform Model Variation	Check BS response per platform	Lower BS average on Platform C. High standard deviation across all platforms.
Machine	Tool to Tool Variation	Check BS response per bonder	Similar response for bonders of the same platform
Material	Device Commonality	Check BS response per device	High CpK observed on device with single/small pads only. Low CpK observed on device with big and small pad.
Method	Varying response on big pad vs. small pad	Check bond program commonality among devices involved	No significant difference observed. High deviation noted for both pad sizes.
Method	No specified location to perform BS test on	Check existing specs; Interviews with operators	No standard BS location being followed

Table 3 shows the verification table used for Chart PC-Al. What is noteworthy about this chart is it consists of devices from the same family yet were found to have differing ball shear response. Deep dive into the ball shear performance of each bond program reveals further dissimilarities.

Table 3. Validation Table for Chart PC-Al

Cat.	Root Cause	Verification Method	Remarks
Man	Operator BS method	Check BS readings uploaded by different operators	No significant impact on BS
Machine	Platform Model Variation	Check BS response per platform	Higher BS average on Platform C. BS Average for Platform A and Platform B ~20gF.
Machine	Tool to Tool Variation	Check BS response per bonder	Higher CpK and smaller deviation seen on Platform B vs. Platform A. Low WIP on Platform C.
Material	Device Commonality	Check similarities and BS response per device	Chart used for one device family
Method	Varying BST response per Bond Program	Extract the unique bond programs in the chart and check their history	Several bond programs with dissimilar BS response. Some bond programs certified with BS readings on the low side.

Root cause verification was also performed for Chart Au-Al (shown in Table 4). The key finding for this chart is that most of the datapoints fluctuate on the low side, regardless of machine or device. Efforts were done to optimize the bond programs involved which did not result in any recovery for the CpK. Hence, additional evaluations were performed to characterize BS response with increasing bonding parameter X and with low-mid-high bonding parameters.

Table 4. Validation Table for Chart Au-Al

Cat.	Root Cause	Verification Method	Remarks
Man	Operator BS method	Check BS readings uploaded by different operators	No significant impact on BS
Machine	Platform Model Variation	Check BS response per platform	Performed series of bond program optimization per platform – CpK not

Machine	Tool to Tool Variation	Check BS response per bonder	recovering; BS response on low side
Material	Device Commonality	Check BS response per device	Most devices have low BS readings (below the mean)
Material	Bond pad location response to BST	Check if ball shear location affects BS score	No significant effect on BS
Method	Insufficient bonding parameter X applied	Validate effect of increasing bonding parameter X and perform risk assessment	↑ Bonding Parameter X = ↑ BS Reading
Method	Varying 1st Bond Parameters	Check BS score when applying Low-Mid-High parameters	↑ Value of Parameters (USG, Time and Force) = ↑ BS Reading – CpK still failing even after re-certification of more robust parameters

2.4 Improve Phase

Based on the results of the validation tables and the characterization of the BS response with the changing factors, five (5) key solutions were generated and further discussed in 3.0 Results and Discussion.

2.5 Control Phase

The effectiveness of each action is continuously monitored in their corresponding control chart. The current setup of the SPC charts alert the engineering team whenever any abnormalities or out-of-control points are detected. Regular monitoring of the CpK of the corresponding charts are also done during area SPC reviews. Moreover, all changes and new processes introduced were documented in specifications along with approval from the change control board. Updated work instructions are also documented herewith.

3.0 RESULTS AND DISCUSSION

3.1 SPC Chart Limits Information System (SPC CharLIS)

During baseline characterization and chart clean-up (as discussed in 2.2.2), it was observed that most of the out-of-control datapoints were due to failing setups. Further probing on this root cause revealed that setup technicians are having difficulty in accessing the accurate SPC limits during setup. This problem requires a more user-friendly alternative to the current SPC reference lookup tool.

Table 5. Why-Why-Why Analysis on Out-of-Control Ball Shear Datapoints

Problem	Why 1	Why 2	Why 3	Why 4	Why 5
Out-of-control BS datapoints	Failing setups / Setup requires re-qualification	Incorrect SPC limits reference during setup	Technicians have difficulty in pulling out SPC chart limits for specific device	Technicians are not familiar with the transactions on existing SPC reference tool	Tedious and time-consuming pull-out process of SPC charts

SPC Chart Limits Information System (SPC CharLIS) is an automated system that pulls out chart information regarding a specific lot. This reduces the current multi-step process that usually takes about 90sec per chart to a one-step process that takes only about 3sec to pull out all corresponding charts for the lot input. This serves as a reliable reference for SPC chart information that helps improve productivity, quality and accessibility in the line.

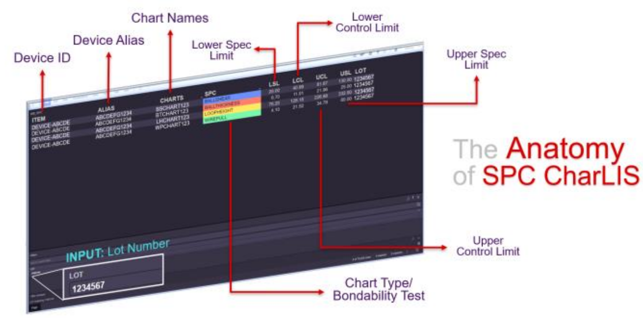


Fig. 3. User interface and anatomy of SPC Chart Limits Information System (SPC CharLIS)

To assess its accuracy, the information pulled out from SPC CharLIS was compared to the information from the reference database. Forty (40) lots were sampled and were verified to be 100% matching.

3.2 Standardized BOAC Ball Shear Method

The validation table for Cu-BOAC charts (Table 2) showed variation among operators, possibly aggravated by the lack of a standardized ball shear methodology deployed in the line. Through several simulations, it was found that the ball shear readings were more consistent when there is an area of the same bond level for the shear tool to rest on. Since it is characteristic of BOAC dies to have elevated bond pad etchings, this factor is significant to the ball shear stability for these devices. Specs update was then performed to document the correct shear tool position at time zero before activating the test button to start shearing.

3.3 Bond Program Standardization

Checking the history of the devices for Chart PC-Al revealed that the ball shear response of their certified bond programs is not standardized (*Fig. 4*). Bond programs showing different and low BS response were identified for optimization, targeting higher BS readings. Given the formula for CpK in Equation 1, it is intuitive to minimize the standard deviation to increase CpK. But looking at the numerator of the equation, there is also opportunity to increase the gap between the mean and the lower spec limit to induce the same effect in the CpK. This propelled the direction during optimization to increase the BS average of the identified bond programs.

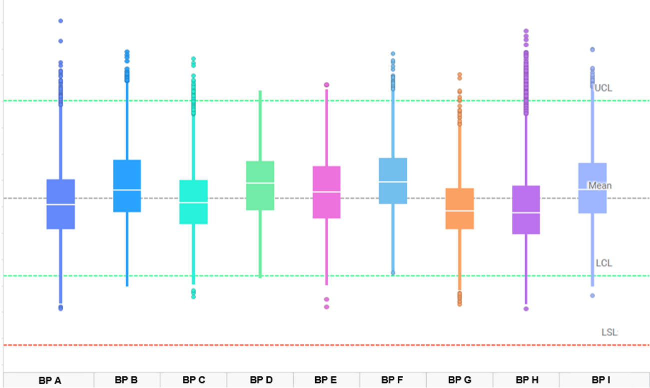


Fig. 4. Box plot of ball shear response per bond program for Chart PC-Al

The newly optimized recipes were re-certified and monitored for effectiveness. For the optimized bond program G, more stable BS response and decrease in standard deviation is already observed (*Fig. 5*), resulting in an increased CpK for this bond program.

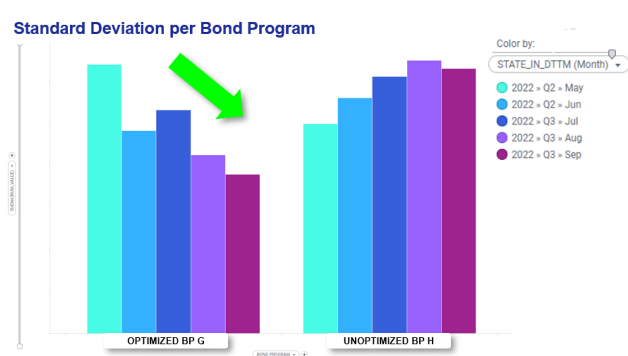


Fig. 5. Month-to-Month Standard Deviation trend for optimized bond program G versus unoptimized bond program H.

3.4 Increasing Bonding Parameter X

While bond program optimization and standardization worked for Chart PC-Al, there have been several optimization attempts for Au on Al devices but still encountering the recurring issue with CpK for Chart Au-Al. It should be noted that while bond program adjustment to increase BS readings is effective, there is a threshold to which first bond adjustments can be made, especially considering the risks for pad cracks on aluminum-pad devices.

From the different root causes explored in Table 4, it is very likely that the current bond parameter X used in production is insufficient. Through One-Way ANOVA (*Fig. 6*), it was validated that increasing bond parameter X makes a significant difference on the ball shear readings.

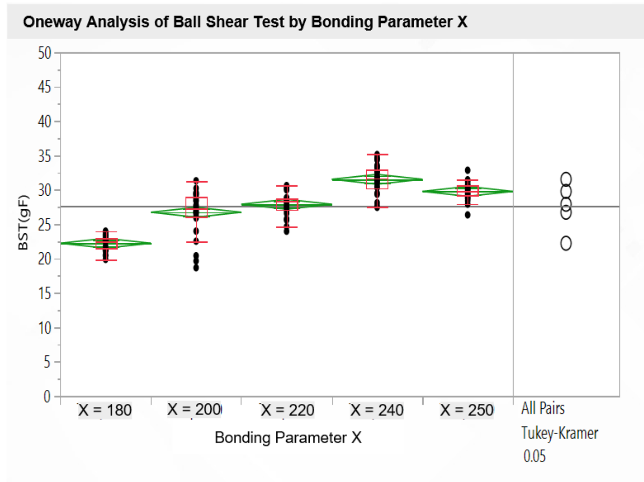
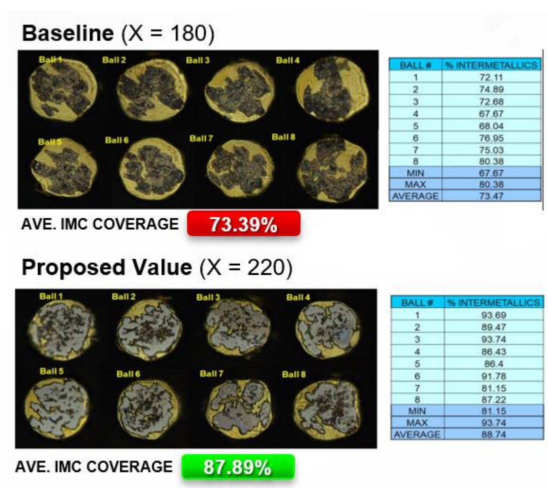


Fig. 6. One-way ANOVA of ball shear readings with increasing bond parameter X.

Further validation of intermetallic coverage shows that we have a better coverage as bond parameter X is increased, signaling better ball adhesion (*Fig. 7*). Through cross section analysis shown in *Fig. 8*, it was observed that IMC layer thickens with increasing bond parameter X—however, the risks of Kirkendall Voiding also increases. Based on these failure analyses, it was determined that bond parameter X = 220 to be the goldilocks value wherein good IMC coverage is realized with minimized risk for voiding.



BALL #	% INTERMETALLICS
1	72.11
2	74.89
3	72.68
4	67.67
5	68.04
6	76.95
7	75.03
8	80.38
MIN	67.67
MAX	80.38
AVERAGE	73.47

BALL #	% INTERMETALLICS
1	93.69
2	89.47
3	93.74
4	86.43
5	86.4
6	91.78
7	81.15
8	87.22
MIN	81.15
MAX	93.74
AVERAGE	88.74

Fig. 7. Intermetallic coverage on units processed at baseline parameters (X = 180) versus units processed with increased bond parameter X (X = 220).

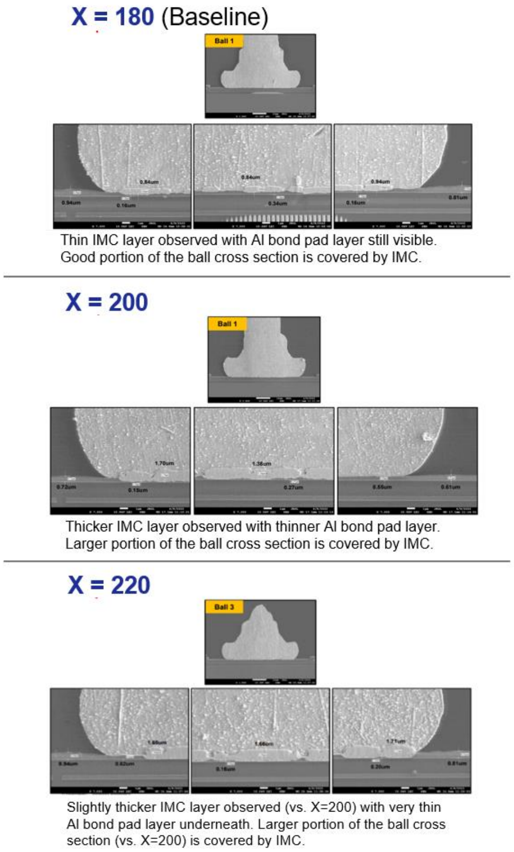


Fig. 8. Cross section analysis on units processed at bond parameter X = 180 (baseline), X = 200, and X = 220, highlighting the Al bond pad thickness.

The increased bond parameter X was applied to lead lots and showed higher mean ball shear reading versus baseline. This translated to passing CpK (2.48) and PpK (1.84), which is significantly higher than the baseline chart Au-Al.

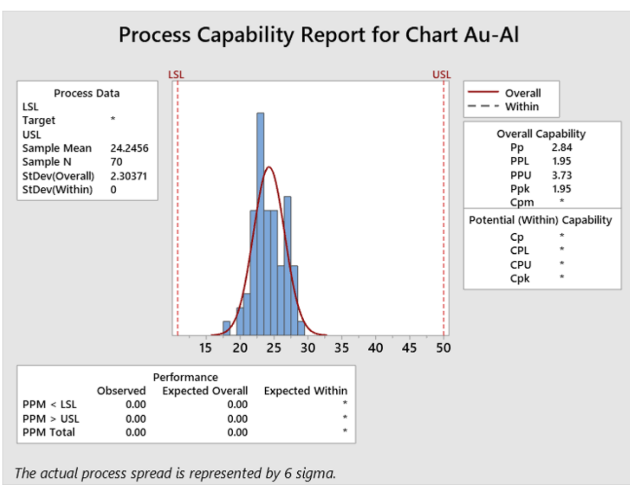


Fig. 9. Process capability analysis on lead lots processed with bond parameter X = 220.

3.5 Shear per Area SPC Charts

Currently, ball adhesion is being measured, recorded and monitored through raw ball shear readings in gF. However, through the course of this study, it was found that ball shear data for Platform C bonders are on the low side of the centerline (Appendix B). Mapping out the differences of Platform C versus the other platforms showed that a different capillary is used specifically for Platform C. This capillary design has a smaller chamfer diameter which results to a smaller ball size and consequently, lower ball shear readings.

With this current configuration, even for the same device, ball size can vary and result to ball shear variation if they are processed from different platforms. The main criteria to determine if the BS reading is passing is the set minimum shear per area for each wire to bond pad metal pair. In fact, this is the reference from which the minimum raw ball shear reading was obtained. An example of this computation is exhibited below.

$$Min\ Ball\ Shear\ Reading\ (gF) = Min. Shear\ per\ Area \cdot Ball\ Area$$
$$= Min. Shear\ per\ Area \cdot \frac{\pi}{4} \cdot \left(Ball\ Diameter \cdot \frac{mil}{25.4\ um}\right)^2$$

$$Min\ Ball\ Shear\ Reading\ (gF) = 6\ {}^{gF}/_{mil^2} \cdot \frac{\pi}{4} \cdot \left(105\ um \cdot \frac{mil}{25.4\ um}\right)^2$$

Based on this concept, the feasibility of shear per area (SPA) charts were explored. SPA charts entailed that the shear per area value would be plotted into SPC charts instead of the raw ball shear readings. This meant that devices of the same wire type and bond pad material can be charted together instead of separating them by wire diameter. As evaluation, the shear per area of all Cu on BOAC devices were recorded and monitored in SPC charts for one (1) week. The resulting process capability is shown in Fig. 10.

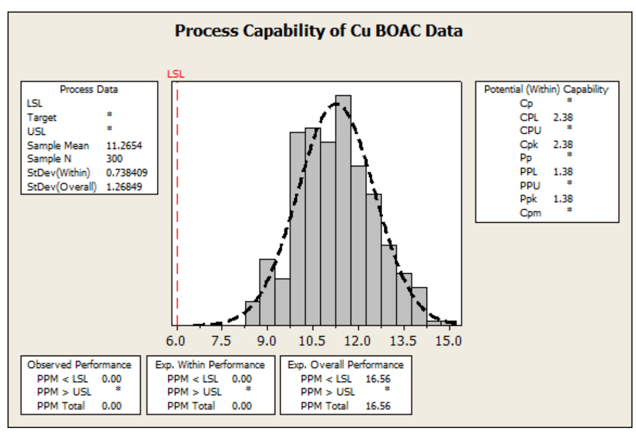


Fig. 10. Process capability analysis on shear per area (SPA) data for Cu/BOAC devices.

The initial SPA data for different Cu on BOAC devices of varying wire sizes resulted in a control chart with passing CpK of 2.38. These results affirm the feasibility of using SPA SPC charts as a more sustainable and manageable way of monitoring ball adhesion strength. This can significantly trim down charts being monitored by 90.48% since there is no need to segregate the charts by wire size.

3.6 Impact of the Ball Shear Variation Reduction Projects

Through the combined initiatives and innovations introduced in this study, strengthened ball adhesion and more robust wire bonding process is expected. The lot rejection rate was decreased by 36.24% for the affected devices. There also is a continued downward trend for lifted ball defects, showing 46% improvement since the actions were implemented (Fig. 11). This also means further reduction in tool downtime, as well as improved mean time between assists and setup success rate.

The projects also led to increased productivity from the 74.38%-time savings per bondability test request. Additionally, approximately US$47K savings per year is expected from the reduced manhours. Further cost avoidance savings is also projected from the reduction of scrapped units due to lifted ball and lifted metal.

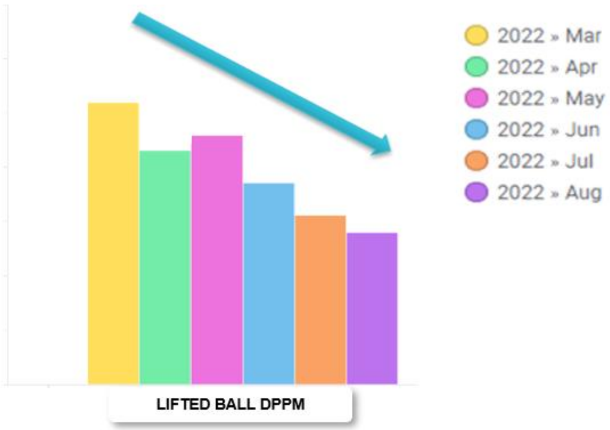


Fig. 11. Lifted ball defective parts per million trend upon implementation of defined actions.

4.0 CONCLUSION

Lean Six Sigma approach to analyze and solve the failing ball shear charts at Wire Bond was pivotal in devising variation reduction innovations to achieve process stability. The use of the DMAIC methodology allowed for comprehensive mapping of all possible root causes and trimming down to the factors with the most impact. The study resulted in an automated SPC information reference tool to reduce man-related variation, standardized ball shear methodology to lessen man- and method-related variations, bond program optimization and standardization as well as increasing bond parameter X to minimize recipe- and method-related variation, and exploring the feasibility of using shear per area charts to address measurement- and method-related variation.

The study proved that through small signals from the SPC charts, it is possible to assess the current process capability and the integrity of the products being put out. Hence, continuous monitoring of control charts—in this case, ball shear charts—ensures that the current setups are within process control and ball-related rejects are minimized.

5.0 RECOMMENDATIONS

It is recommended to create a web-application for SPC CharLIS for ease of access and increase possibility of fan out to other areas and manufacturing sites. Further studies on the use of shear per area (SPA) charts is also recommended to be pursued on other wire type and bond pad material combinations. Additionally, an in-depth time study on the procedure to obtain the shear per area readings would also be helpful to assess whether the time saved from the reduced number of charts would compensate for the additional activity during bond test.

7.0 ACKNOWLEDGMENT

The team expresses their utmost gratitude to the wire bond SPC quality improvement team who have provided inputs and have worked fervently to help solve process control related issues in the line. Thanks is also due to the management team who have supported the team in the execution and implementation of the solutions and innovations presented in this paper. Great appreciated is also given to the manufacturing team for supporting the evaluations made throughout the course of this study.

8.0 REFERENCES

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9.0 ABOUT THE AUTHORS

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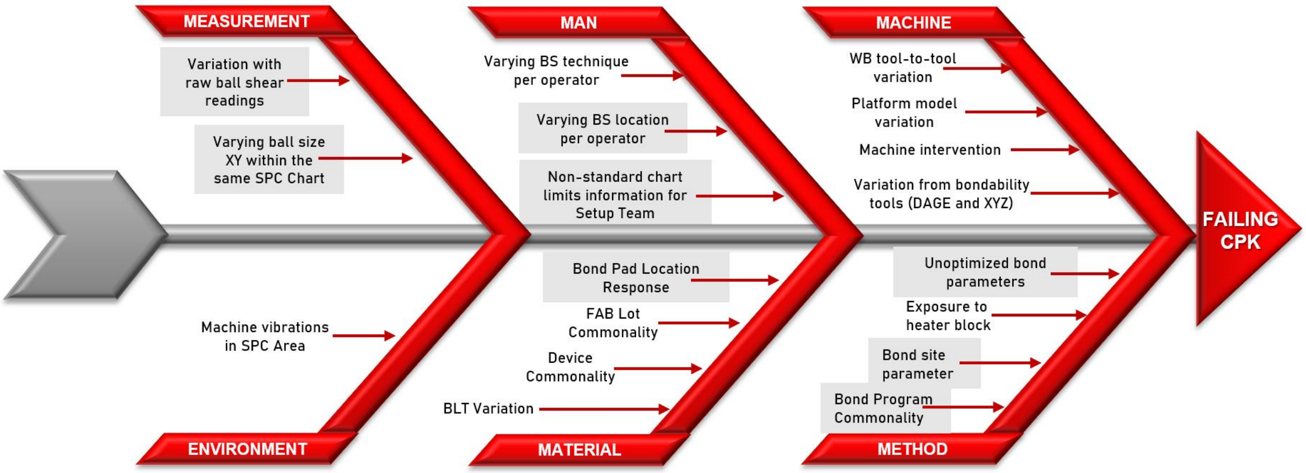
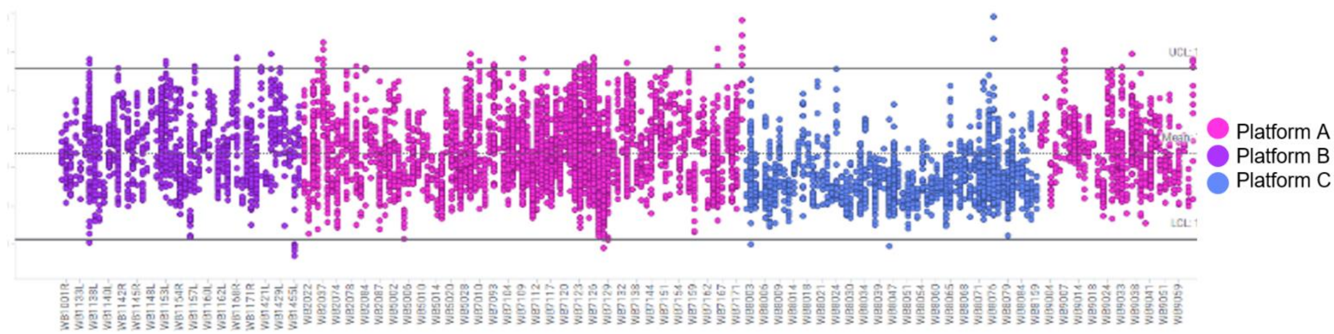
10.0 APPENDIX



Appendix A. Fishbone diagram of all possible man-, machine-, material-, method-, measurement-, and environment-related factors contributing to failing CpK of ball shear charts.



Appendix B. Scatter plot of ball shear readings per tool and categorized according to the tool platform used.