MODEL "S" YIELD IMPROVEMENT THROUGH FAILED ADJUST REJECT REDUCTION

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ABSTRACT

The current trends of manufacturing industries are expected to face economic uncertainty driven by supply chain disruptions, constant workforce job-hopping, and economic recessions. The role of the New Production Introduction Team, aside from developing a cost-effective product design, is vital to combat the negative impact of those uncertainties by introducing breakthrough ideas for process controls and procedures that are resistant to frequent changes and disruptions in the assembly line. This is crucial to achieve the best quality performance, reduce or eliminate scrap, and increase productivity.

This paper discusses the utilization of various Engineering solutions and statistical analysis tools at Knowles Electronics Philippines to effectively improve the yield performance of Model S thereby greatly improving the company's financial status in terms of scrap cost. Actions and lessons learned in this paper were then set as a baseline for future NPI projects.

1.0 INTRODUCTION

The concept of Balanced Armature (BA) drivers lies in the principle of electromagnetism which uses an electrical domain to vibrate a tiny metal reed that serves as the mechanical domain connected to a thin metal sheet to produce an acoustical domain. Figure 1 illustrates the fundamental concept of BAs.

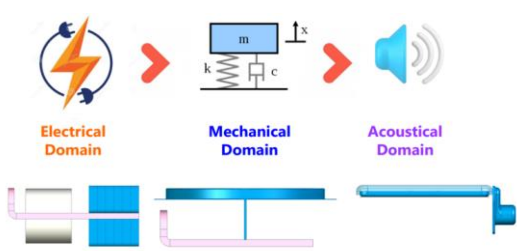


Fig 1. Balanced Armature Driver Energy Transfer Illustration

Balanced Armature (BA) drivers are used for a wide range of applications in Medical Technology and Specialty Audio and one of the major components of hearing aids, earphones, and in-ear monitors (see Figure 2).

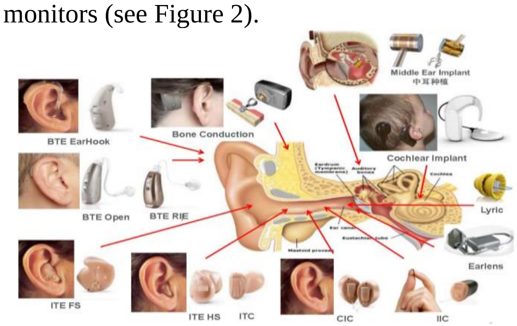


Fig 2. Application of Balanced Armature (BA) Drivers

A BA driver must maintain an ideal balance between its components, especially the gap between magnets and reed to provide the best acoustic performance as shown in Figure 3. Each component has its unique function and the tiniest error in its assembly could deteriorate the sound it produces.

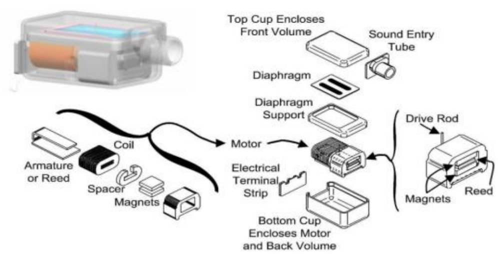


Fig 3. Major Components of Balanced Armature (BA) Drivers

To make a BA driver functional, it needs to be adjusted to the desired set point so that it can produce the targeted sound pressure level. A functional test is then conducted that sweeps through different acoustic parameters that are critical to the customer.

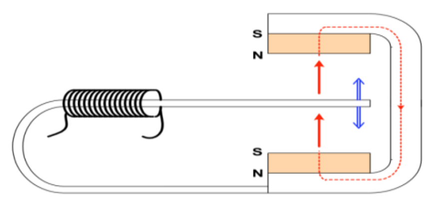


Fig 4. Illustration of Electro-mechanical Adjustment of BA Driver

If a BA driver cannot be adjusted, it will not be responsive during acoustic testing and will be rejected as *"Failed Adjust"*, which means that there is a problem causing the reed and other components not to move properly.

In this paper, a series of structured analyses utilizing Lean Six Sigma principles, and DMAIC methodology was utilized to significantly reduce the Failed Adjust rejection on Model S.

2.0 REVIEW OF RELATED WORK

Not applicable

3.0 METHODOLOGY

This paper utilizes the DMAIC methodology to effectively reduce the Failed Adjust rejection of Model S.

3.1 DMAIC – Define Phase

3.1.1 Problem Statement

As shown in Figure 5, Model S is having low yield rate performance with only 84.2% for January 2023, which is off its monthly target of 88.0%.

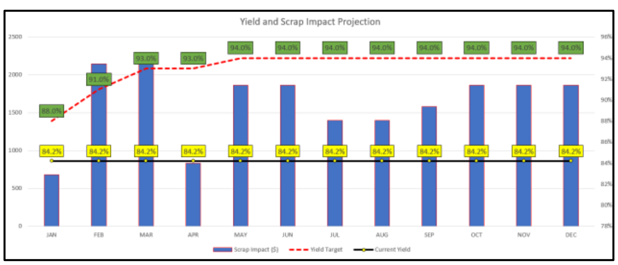


Fig 5. Model S yield performance and target

3.1.2 Project Objective

To avoid further scrap penalties, Failed Adjust (FA) rejection must be decreased by half to increase the yield performance of Model S from 84.7% to 94.0% until the end of March 2023.

3.2 DMAIC – Measure

3.2.1 Yield Performance

The average yield performance of Model S based on Oracle Vigilance Analytics Data is only at 84.23%, which is off by 3.4% from the January target of 88.0% (Figure 6).

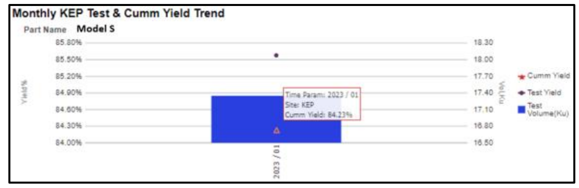


Fig 6. Model S Yield Performance

Based on the Pareto of failures (Figure 7), the main contributor to this low yield performance is Failed Adjust (FA) reject at 13.63% rejection rate, which comprises 92% of the overall rejects for Model S.

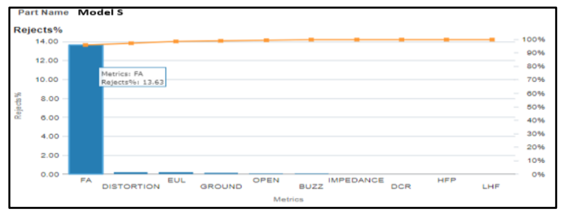


Fig 7. Pareto of Rejects for Model S

3.2 DMAIC – Analyze

On the macro process flow chart below (Figure 8), Failed Adjust (FA) is detected on the Adjust and Test Process where the acoustic testing is being performed.

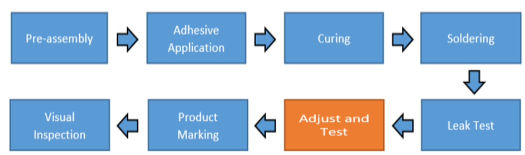


Fig 8. Model S Process Flow Chart

By formulating a fishbone diagram (Figure 9) through Cross-Functional Team brainstorming, obtaining significant inputs from the PFMEA, and adopting lessons learned from other models, several potential root causes have been listed below based on the various 5Ms + 1E (measurement, material, man, method, machine, environment).

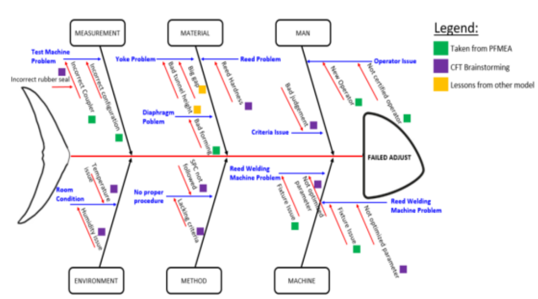


Fig 9. Fishbone Diagram for Failed Adjust

Before root cause validation, a screening was performed by rating it from (1) as the lowest and (5) as the highest on its likeliness to occur and the complexity of validation. All causes with a product of fifteen (15) and above will be prioritized during validation as reflected in Table 1.

Table 1. Potential Root Cause Screening Prioritization

Factor	Potential Root Causes	Rating	Score
Machine	Not optimized reed welding parameter	VV	25
Measurement	Mismatched rubber sea	SV	15
Material	Reed hardness	VS	15
Material	Yoke gap	SS	9
Machine	Not optimized shim welding parameter	SS	9
Method	Lacking criteria	NV	9
Measurement	Incorrect configuration	NV	5
Environment	Temperature issue	NV	5
Environment	Humidity issue	NV	5
Material	Bad yoke tunnel height	NV	5
Man	Not certified operator	NV	5
Man	New operator	NV	5
Method	SPC not followed	NS	3
Machine	Reed welding fixture issue	SN	3
Machine	Shim welding fixture issue	SN	3
Man	Bad judgement	SN	3
Material	Diaphragm forming issue	NN	1

Occurrence	Score	Complexity	Score
V = Very Likely	5	V = Very Easy	5
S = Somewhat Likely	3	S = Somewhat Easy	3
N = Not Likely	1	N = Not Easy	1

3.2.1 Root Cause Validation

3.2.1.1 Machine: Reed Welding Machine Parameter Not Fully Optimized

The current parameter of reed welding is set based on three factors which are: Power, Weld Force (Left), and Weld Force (Right). Further understanding the product's mechanism, it then came into consideration to include the position of the welding point as one of the parameters.

The product structure follows the concept of a cantilever beam (Figure 10) where the weld point serves as the fixed end and the tip of the reed serves as the free end.

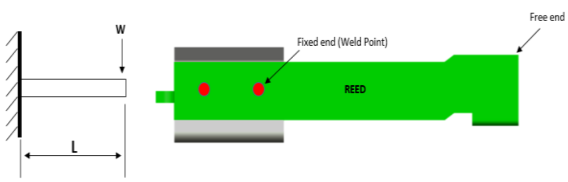


Fig 10. Comparison of a Cantilever Beam to BA Product Construction

3.2.1.1.1 Data Gathering

One week of data on welding position from Electronic Statistical Process Control (E-SPC) (Appendix A) was obtained to be correlated to the daily rejection rate of Failed Adjust (FA).

3.2.1.1.2 Validation

3.2.1.1.2.1 Normality Test

Normality testing (Figure 11) showed that the P-value is at 0.935, which is higher than the set alpha level of 0.05, thus, the test result failed to reject the null hypothesis (H_o) and validated that the data gathered for welding location follows the normal distribution.

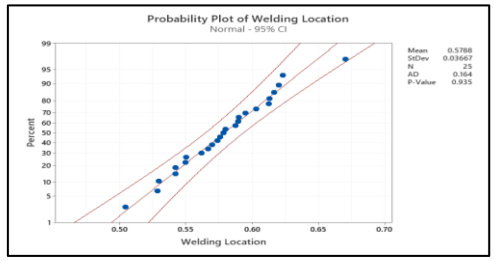
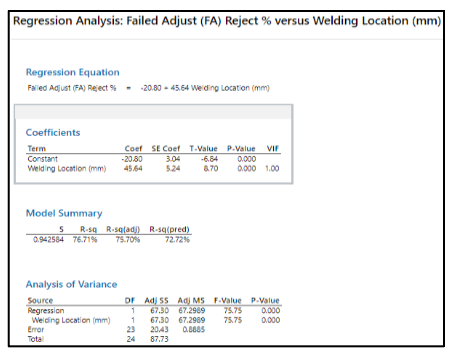


Fig 11. Probability Plot of Welding Location

3.2.1.1.2.2 Regression Analysis

The regression model as shown in Figure 12, shows a P-value of 0.000, which is lower than the alpha level of 0.05, thus, the Null Hypothesis (H_o) is rejected and confirmed that the relationship between Failed Adjust (FA) rejection and Welding Location is statistically significant.


Regression Analysis: Failed Adjust (FA) Reject % versus Welding Location (mm)

Regression Equation

Failed Adjust (FA) Reject % = -20.80 + 45.64 Welding Location (mm)

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-20.80	3.04	-6.84	0.000	
Welding Location (mm)	45.64	5.24	8.70	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.942584	76.71%	75.70%	72.72%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	67.30	67.2989	75.75	0.000
Welding Location (mm)	1	67.30	67.2989	75.75	0.000
Error	23	20.43	0.8885		
Total	24	87.73			

Fig 12. Regression Analysis Result of Welding Location and Failed Adjust

3.2.1.1.3 Root Cause Conclusion

Based on the statistical analysis conducted, it is concluded that welding location is a valid root cause of Failed Adjust (FA) rejection.

3.2.1.2 Measurement: Mismatched Rubber Seal

The rubber seal is used to prevent air leakage from the Balanced Armature (BA) driver to the coupler. It also ensures a smooth flow of acoustic signal into the testing machine. The illustration in Figure 13 shows how the BA driver is integrated into the coupler.

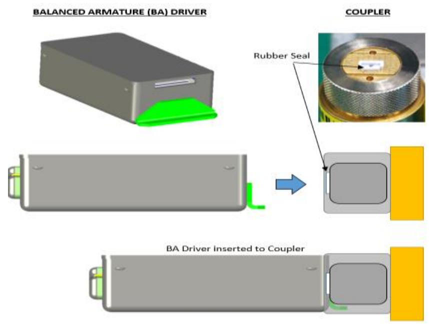


Fig 13. BA Receiver and Coupler Integration

3.2.1.2.1 Data Gathering

It was found that the current coupler is using an old design rubber seal which has a circular hole with only 0.0962 mm² compared to the BA Receiver hole which is at 0.767 mm² (Figure 15). This shows that there is a partial blockage of acoustic signals due to the shape of the rubber seal hole.

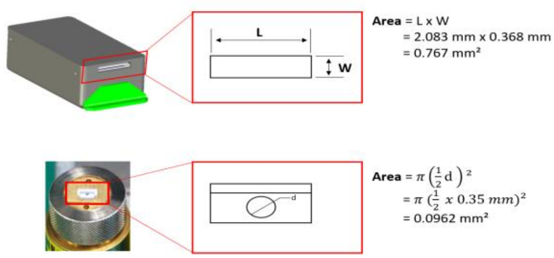


Fig 14. BA Receiver and Rubber Seal Airflow Area Computation

3.2.1.2.2 Validation

Checking the acoustic response graph (Figure 15) of the BA driver, we can observe that there is a glitch near Peak 2. This signifies that the issue is most probably related to air tubing or path.

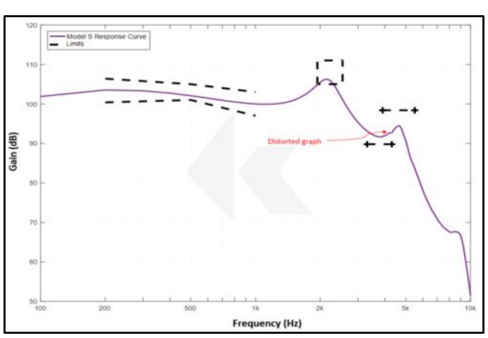


Fig 15. Electroacoustic Response Graph of Model S

3.2.1.2.3 Root Cause Conclusion

It is concluded that the rubber seal used is mismatched with the BA Receiver and is a valid root cause of Failed Adjust (FA) rejection.

3.2.1.3 Material: Difference in Reed Hardness

A BA driver is essentially a complicated Spring-Mass system where:

Mass (m)	= amount of "stuff" that moves,
Stiffness (k)	= summation of all "springs" in the system
Damping (B)	= friction and other losses
Force (f)	= the electric signal moving on the coil
Distance (x)	= the displacement of armature

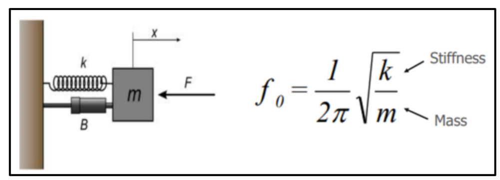


Fig 16. Illustration of Spring-Mass System

The reed functions as the spring, in which its material integrity, especially its hardness, is very important to the BA driver's electro-acoustic performance.

3.2.1.3.1 Data Gathering

During failure analysis, it was observed that good units have larger granular pattern compared to the bad units as shown in Figure 17.

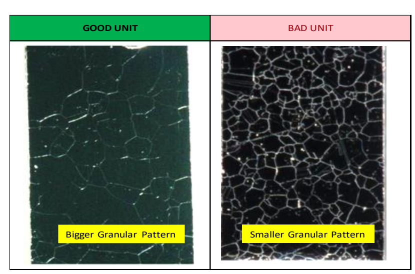


Fig 17: Illustration of Grain Pattern

A hardness test (Appendix B) is conducted in each unit for further verification.

3.2.1.3.2 Validation

3.2.1.3.2.1 Normality Test

The results shown in Figure 18 reflect that the P-value of reed hardness for Good units and Bad units are at 0.058 and 0.067, which are higher than the set alpha level of 0.05, thus, the test failed to reject the null hypothesis (H_o) and validated that the data gathered for Reed Hardness on both materials follow the normal distribution.

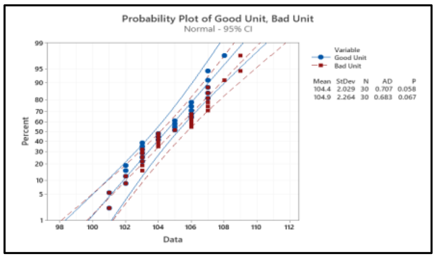


Fig 18: Normality test for Reed Hardness of Good and Bad units

3.2.1.3.2.2 Hypothesis Testing – 2-sample t-Test

Performing a 2-sample t-test (Figure 19) resulted in a P-Value of 0.227, which is higher than the set alpha level of 0.05, thus, the test result failed to reject the null hypothesis (H_o) and confirmed that there is no significant difference between the mean of reed hardness of Good units and Bad units.

Two-Sample T-Test and CI: Good Unit, Bad Unit

Sample	N	Mean	StDev	SE Mean
Good Unit	30	104.47	2.08	0.38
Bad Unit	30	105.17	2.35	0.43

Estimation for Difference

Difference	95% CI for Difference
-0.700	(-1.847, 0.447)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-1.22	57	0.227

Fig 19. Hypothesis Testing – 2-Sample t-Test for Reed Hardness of Good and Bad units

3.2.1.3.3 Conclusion

It is concluded that the reed hardness is not a valid root cause for Failed Adjust (FA) rejection.

4.0 RESULTS AND DISCUSSION

4.1 Root Cause Validation Summary

After a series of validation activities, there were remaining two (2) valid Potential Root Causes as shown in Table 2. The other validation results of the other factors can be found in the Appendix Section.

Table 2. Root Cause Validation Table Summary

Element	Potential Root Causes	Verification	Target	Result	Status	Remarks
Material	Bad SFY Tunnel Height	Check actual tunnel height in comparison to print specification	20-Jan	Invalid	Closed	All are within specification
	Big dovetail gap	Run evaluation small gap and bigger gap	22-Jan	Invalid	Closed	No significant difference on the result of both condition
	Bad OPD Forming	Run samples with limit bad forming to perfect forming material	21-Jan	Invalid	Closed	No significant difference on the result of both condition
	Reed hardness issue	Run evaluation for different grain condition of reed	22-Jan	Invalid	Closed	No significant difference on the result of both condition
Man	Bad judgement on visual criteria	Conduct MSA on operator's visual judgement	22-Jan	Invalid	Closed	Operator passed the MSA
	New operator	Confirm operator's training record	18-Jan	Invalid	Closed	Veteran operator's running in RAI
	Operator not certified	Confirm operator's training record	18-Jan	Invalid	Closed	Operator's are trained and certified
Method	ESPC not followed	Confirm ESPC data	22-Jan	Invalid	Closed	ESPC is performed and updated
	Lacking criteria	Confirm machine IPQC if can filter misalignment of camera	26-Jan	Invalid	Closed	Camera alignment checking is included in PFMEA
Machine	Reed Welding Machine parameter not fully optimized	Confirm history of reed welding parameters implemented	29-Jan	Valid	Closed	Reed welding parameters not fully optimized
	Reed Welding Fixture issue	Check buy off history of reed welding	27-Jan	Invalid	Closed	Reed welding buy-off passed
	Shim Welding Fixture issue	Check buy off history of reed welding	27-Jan	Invalid	Closed	Shim welding buy-off passed
	Shim Welding Machine parameter not fully optimized	Confirm history of reed welding parameters implemented	29-Jan	Invalid	Closed	Machine parameters are optimized
Measurement	Incorrect FCAAT fixture	Confirm actual FCAAT fixture	22-Jan	Invalid	Closed	Correct FCAAT fixture used
	Incorrect FCAAT coupler	Confirm actual FCAAT coupler	22-Jan	Invalid	Closed	Correct FCAAT coupler used
	Incorrect Rubber seal	Confirm actual FCAAT rubber seal	22-Jan	Valid	Closed	Rubber seal shape is does not coincide with the sound port
	Mistake test configuration	Confirm actual FCAAT test configuration	22-Jan	Invalid	Closed	Correct FCAAT test configuration used
Environment	Temperature Issue	Confirm historical temperature data	20-Jan	Invalid	Closed	No significant changes on the temperature data
	Humidity Issue	Confirm historical humidity data	20-Jan	Invalid	Closed	No significant changes on the humidity data

4.2 DMAIC – Improve

4.2.1 Mismatched Rubber Seal

Using the SCAMPER method (Figure 20), the rubber seal was modified from a circular shape to a rectangular shape to match the BA driver.

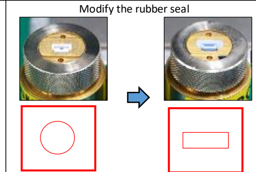
SCAMPER	Proposal	Responsible
Substitute		
Combine		
Adapt		
Modify	Modify the rubber seal  Circular / Rectangular	Jerry A.
Put to Other Uses		
Eliminate		
Rearrange		

Fig 20. SCAMPER Table for Rubber Seal Improvement

4.2.1.1 Validation

The electroacoustic response graph in Figure 21 shows the comparison between circular rubber seal and rectangular rubber seal. It is observed that the glitch on the graph found on the circular rubber seal (yellow curve) at 2nd peak is eliminated in the graph of the rectangular rubber seal (purple curve).

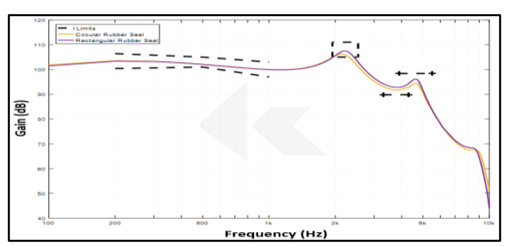


Fig 21. Electro Acoustic Response Graph of Model S using Circular Rubber Seal and Rectangular Rubber Seal

Small scale validation run shows that the Failed Adjust (FA) rejection decreased from 15.0% to 6.4% as shown in Figure 22.

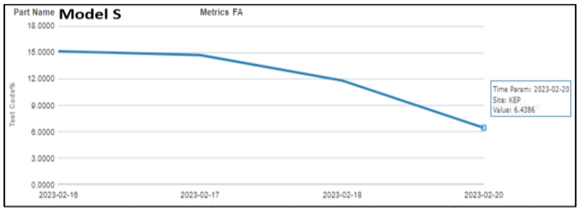


Fig 22. Model S Failed Adjust (FA) Rejection Trend

4.2.2 Not Optimized Reed Welding Parameter

4.2.3.1 Design of Experiment – Full Factorial

A full factorial design is performed based on the design as shown in Figure 23 and using four factors shown in Table 4.

Design Summary

Factors:	4	Base Design:	4, 16
Runs:	33	Replicates:	2
Blocks:	1	Center pts (total):	1

Fig 23. Full Factorial Design Summary of Reed Welding

Table 3. List of Factors for Reed Welding DOE

Factor	Name	Type	Low	High
A	Weld Energy	Numeric	3	7
B	Weld Force (Left)	Numeric	1	3
C	Weld Force (Right)	Numeric	1	3
D	Weld Location	Numeric	0.5	0.7

Based on the Analysis of Variance (Figure 24), the model has a P-Value of 0.008 which confirms that the model is significantly the same with Factor A (Weld Energy), Factor D (Weld Location), and the 2-way interaction of Factors A and D.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	0.023950	0.002177	11.06	0.008
Linear	4	0.017541	0.004385	22.28	0.002
Weld Energy	1	0.007132	0.007132	36.23	0.002
Weld Head Force (Left)	1	0.001278	0.001278	6.49	0.051
Weld Head Force (Rigth)	1	0.000371	0.000371	1.88	0.228
Welding Location	1	0.008761	0.008761	44.50	0.001
2-Way Interactions	6	0.004525	0.000754	3.83	0.081
Weld Energy*Weld Head Force (Left)	1	0.000022	0.000022	0.11	0.754
Weld Energy*Weld Head Force (Rigth)	1	0.000653	0.000653	3.32	0.128
Weld Energy*Welding Location	1	0.002916	0.002916	14.81	0.012
Weld Head Force (Left)*Weld Head Force (Rigth)	1	0.000759	0.000759	3.86	0.107
Weld Head Force (Left)*Welding Location	1	0.000164	0.000164	0.83	0.403
Weld Head Force (Rigth)*Welding Location	1	0.000012	0.000012	0.06	0.818
Curvature	1	0.001884	0.001884	9.57	0.027
Error	5	0.000984	0.000197		
Total	16	0.024934			

Fig 24. Analysis of Variance of Factors

4.2.3.2 Response Optimization

The solution (Figure 25) shows a possible minimum Failed Adjust (FA) rejection of 5.28% with a Composite Desirability of 91.33%

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Failed Adjust Rejection	Minimum		0.0415	0.1718	1	1

Solution

Solution	Weld Energy	Weld Head Force (Left)	Welding Location	Failed Adjust Rejection Fit	Composite Desirability
1	5	2	0.6	0.0528	0.913277

Multiple Response Prediction

Variable	Setting
Weld Energy	5
Weld Head Force (Left)	2
Welding Location	0.6

Response	Fit	SE Fit	95% CI	95% PI
Failed Adjust Rejection	0.0528	0.0164	(0.0167, 0.0889)	(0.0017, 0.1039)

Fig 25. DOE Response Optimization Result

A one (1) week validation run shows that the Failed Adjust (FA) rejection decreased from 4.0% to 2.0% as shown in Figure 26.

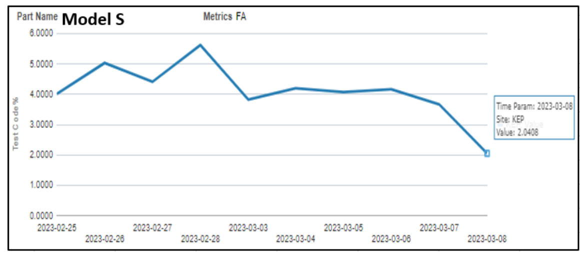


Fig 26. Model S Failed Adjust (FA) Rejection Trend

A series of validations and improvements led to a reduction of Failed Adjust (FA) rejection from 13.63% to 4.94%, which is a total of 63.76% improvement as shown in Figure 27.

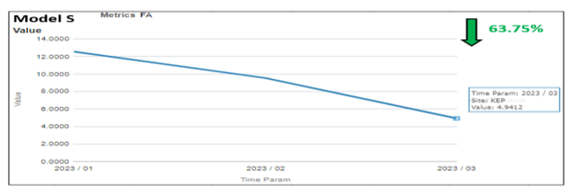


Fig 27. Failed Adjust (FA) Rejection Trend (January to March 2023)

This contributes to an increase in yield rate for Model from 84.2% to 93.1%, which is a total of 10.57% improvement as shown in Figure 28.

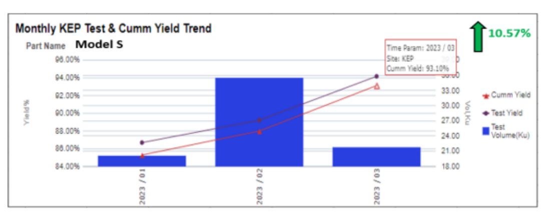


Fig 28. Model S Yield Trend (January to March 2023)

The improvements helped the company save $19,500 for scrap cost avoidance.

4.2 DMAIC – Control

With a series of root cause validations and improvements, it is a must to standardize and document all lessons learned and actions that have been implemented. The PFMEA (Figure 29) was updated to include that the proper rubber seal should be used for Model S with an RPN of 64.

No.	Process Step/ Function	Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Classification	Potential Cause(s) of Failure	Current Process: Controls Prevention	Current Process: Occurence	Current Process: Controls Detection	Detection	RPN	Recommended Action
36	Adjust and Test	Good Units	Over Rejection	Distortion, LLF	8		Worn-out pogo pins	PM Monitoring	2	OQC Sampling check, Golden Sample Checking, SUV, Preventive Maintenance, Calibration, 100% Functional Test	4	64	No action required
				Distortion	8		Incorrect fixture setup	Certified operators	2	OQC Sampling check, Golden Sample Checking, SUV, Preventive Maintenance, Calibration, 100% Functional Test	4	64	No action required
				Failed Adjust 5	8		Incorect rubber seal used	Certified operators Indicate in work instruction	2	OQC Sampling check, Golden Sample Checking, SUV, Preventive Maintenance, Calibration, 100% Functional Test	4	64	No action required

Fig 29. Updated PFMEA of Model S

In addition, the Reed Welding Recipe (Figure 30) has also been updated to standardize the use of optimized parameters.

EQUIPMENT PARAMETER MATRIX

REED WELD MACHINE

Check Items		Reed Weld MODEL A	Reed Weld MODEL B	Reed Weld MODEL C	Reed Weld MODEL S
Parameter Setting	Weld head force (left)				2.0 +/- 0.5
	Weld head force (right)				2.0 +/- 0.5 2
	Energy				5.0 +/- 1.0
2	Weld Location				0.6 +/- 0.05
Mechanical Setting	*Z Axis				N/A
	*X Axis				N/A
	*Y Axis				N/A
Output Check	Weld strength				minimum: 5 lbf
Visual Check	Weld position				N/A
	Electrode condition				N/A N/A N/A
	Reed magnet post condition				N/A
Visual Check	Weld Condition				No weld balls
Visual Check	Reed Tine (after trimmer)				Must not bent and no bari
Visual Check	Electrode condition				Left and Right electrode must be align.
Visual Check	Electrode condition				Tip not worn out (Left)
Visual Check	Electrode condition				Tip not worn out (Right)

Fig 30. Updated Equipment Parameter Matrix

5.0 CONCLUSION

The objective to reduce the rejection rate of Failed Adjust (FA) on Model S balanced armature driver by half was successfully achieved through the effective use of a structured Lean Six Sigma methodology and supported by statistical analysis. This was attained by improving the rubber seal design and effectively optimizing the reed weld process parameters to significantly reduce the Failed Adjust failure rate.

6.0 RECOMMENDATIONS

In a fast-paced industry where resolving the problem is of utmost priority, it is highly recommended to perform thorough Root Cause Screening before conducting factor validation. This is to immediately identify and resolve the main causes of the problem while validating less priority causes. It is also imperative that a structured analysis approach be performed through the use of problem-solving techniques supported by statistical tools to address the failures and define appropriate countermeasures.

7.0 ACKNOWLEDGMENT

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8.0 REFERENCES

1. Knowles Electronics, LLC, Itasca, IL, USA, (2023). What is Balanced Armature? https://www.knowles.com/applications/ear-solutions/premium-sound/what-is-balanced-armature

2. LibreTexts Physics, California State University, (2023). The Motion of a Spring-Mass System https://phys.libretexts.org/Bookshelves/University_Physics/

9.0 ABOUT THE AUTHORS

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10.0 APPENDICES

Appendix A – Weld Location vs Failed Adjust Reject %

Welding Location (mm)	Failed Adjust (FA) Reject %
0.5044	2.0%
0.6122	7.0%
0.5295	3.7%
0.5420	4.4%
0.6228	5.9%
0.6026	5.8%
0.5781	4.6%
0.5738	4.9%
0.5502	4.6%
0.5797	4.6%
0.6702	10.0%
0.6201	9.1%
0.5496	4.1%
0.5757	4.8%
0.5892	5.4%
0.5284	4.1%
0.5897	5.3%
0.6129	8.7%
0.5871	6.2%
0.5419	4.1%
0.5616	5.1%
0.6164	9.4%
0.5697	5.4%
0.5949	5.2%
0.5665	6.0%

Appendix B – Hardness Test Results

Sample	Good Unit	Bad Unit
1	102	107
2	107	102
3	107	101
4	105	107
5	106	103
6	106	106
7	103	101
8	101	102
9	106	107
10	108	105
11	105	106
12	103	106
13	107	109
14	106	106
15	104	106

Sample	Good Unit	Bad Unit
16	101	109
17	102	107
18	102	109
19	105	103
20	103	107
21	104	103
22	106	104
23	103	103
24	108	104
25	103	106
26	107	108
27	104	104
28	102	103
29	103	107
30	105	104

Appendix C – Other Root Cause Validation

10.2 Other Root Cause Validation

10.2.1 Material: Big yoke gap

The Pairwise Pearson Correlation Method for Yoke Gap and Failed Adjust (FA) rejection (Figure 31) resulted in a P-Value of 0.321, which is higher than the set alpha level of 0.05, thus, the test result failed to reject the Null Hypothesis (H_o) and confirmed that the Yoke Gap does not have significant correlation and is not a valid root cause of Failed Adjust (FA) rejection.

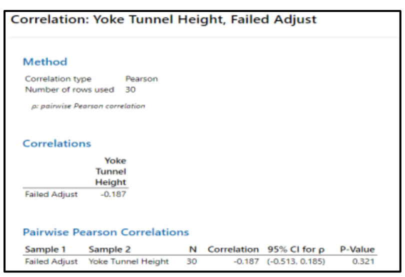


Fig 31: Pairwise Pearson Correlation Method Result for Yoke Tunnel Height and Failed Adjust (FA) Rejection

10.2.2 Machine: Not Optimized Shim Welding Parameter

The Process Capability Shim Weld Strength (Figure 32) has a Ppk of 1.34, which is higher than the standard Ppk requirement of 1.33, thus, indicating that the set parameter for the shim welding process is optimized and not a valid root cause of Failed Adjust (FA) rejection.

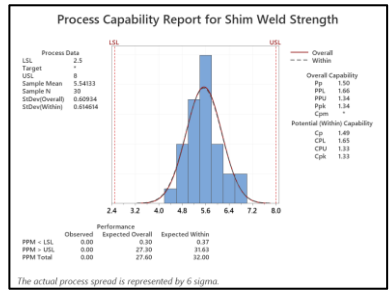


Fig 32: Process Capability Result of Shim Weld Strength

10.2.3 Method: Lacking Reed Welding Criteria

The Control Plan of Model S (Figure 33) shows that all critical parameters of the Reed Welding process are already included on the SPC, thus, the lack of Reed Welding Criteria is not a valid root cause of Failed Adjust (FA) rejection.

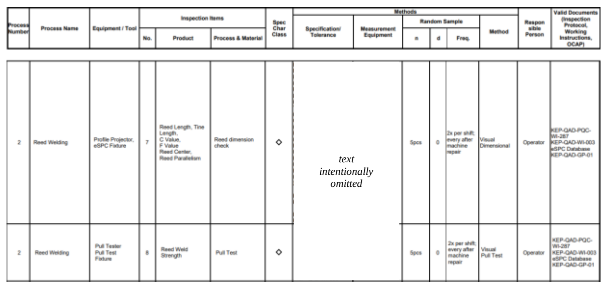


Fig 33: Control Plan of Model S

10.2.4 Measurement: Incorrect Configuration

The test configuration of Model S indicated on the Knowles Test Specification Database System matches with the correct part number for Model S as shown in Figure 34.

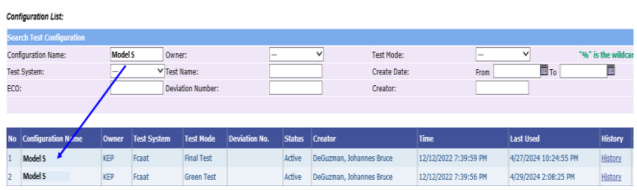


Fig 34: Test Specification Database System Result

10.2.5 Environment: Temperature and Humidity Issue

A one (1) week data of production room temperature and humidity are gathered and plotted into a Time Series Plot. There is no abnormal spike observed for Room Temperature Time Series Plot (Figure 35) as well as for Room Humidity (Figure 36) and all data are within the specified limits. This confirms that there are no issues with room temperature and humidity and validated that these are not valid root causes of Failed Adjust (FA) rejection.

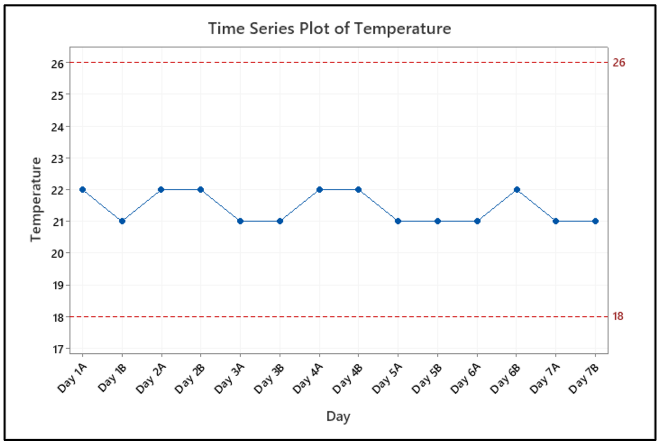


Fig 35: Time Series Plot of Production Room Temperature

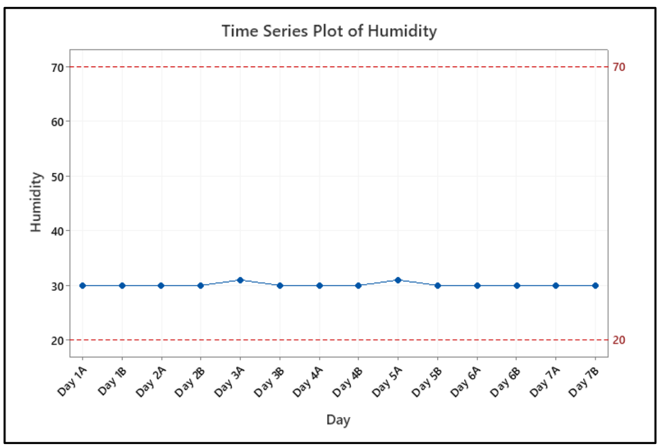
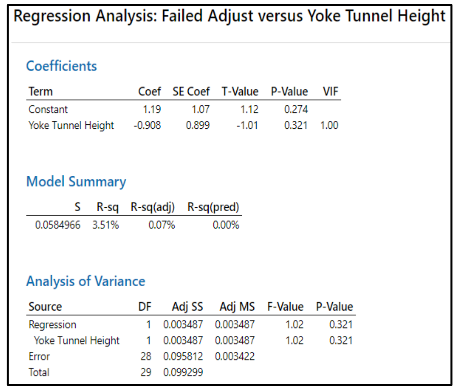


Fig 36: Time Series Plot of Production Room Humidity

10.2.6 Material: Bad Yoke Tunnel Height

Regression analysis for Yoke Tunnel Height and Failed Adjust (FA) rejection (Figure 37) resulted in a P-Value of 0.321 which is higher than the set alpha level of 0.05, thus, the test result failed to reject the Null Hypothesis (H_o) and confirmed that the Yoke Tunnel Height is not a valid root cause of Failed Adjust (FA) rejection.


Regression Analysis: Failed Adjust versus Yoke Tunnel Height

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.19	1.07	1.12	0.274	
Yoke Tunnel Height	-0.908	0.899	-1.01	0.321	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0584966	3.51%	0.07%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.003487	0.003487	1.02	0.321
Yoke Tunnel Height	1	0.003487	0.003487	1.02	0.321
Error	28	0.095812	0.003422		
Total	29	0.099299			

Fig 37: Regression Analysis of Yoke Tunnel Height and Failed Adjust (FA) Rejection

10.2.7 Man: New and Certified Operators

It is confirmed that all operators running in Model S are trained and certified based on the Operators Training and Certification Card (Figure 38), thus, the uncertified operator is not a valid root cause of Failed Adjust (FA) rejection.

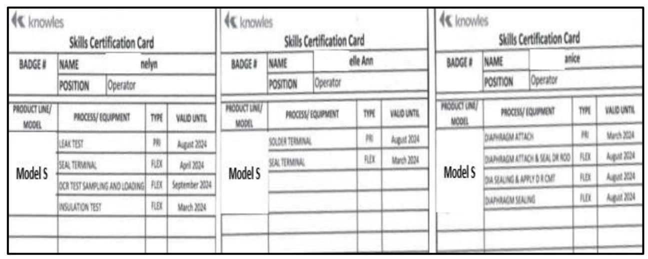


Fig 38: Model S Operator's Certification Card

10.2.9 Method: Statistical Process Control Not Followed

The SPC record below (Figure 39) shows that the SPC for Model S is properly executed therefore it is not a valid root cause of Failed Adjust (FA) rejection.

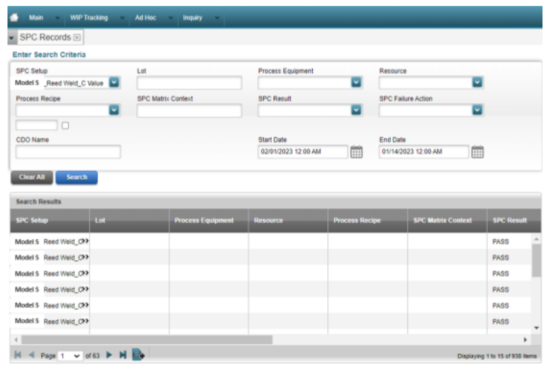


Fig 39: SPC Record for Model S

10.2.10 Machine: Reed Welding Fixture Issue

The Reed welding fixture machine passed the buy-off requirement of Knowles, as shown in Figure 40, with a Ppk of above 1.33, thus, there is no issue on the reed welding fixture, and confirmed that it is not a valid root cause of Failed Adjust (FA) rejection.

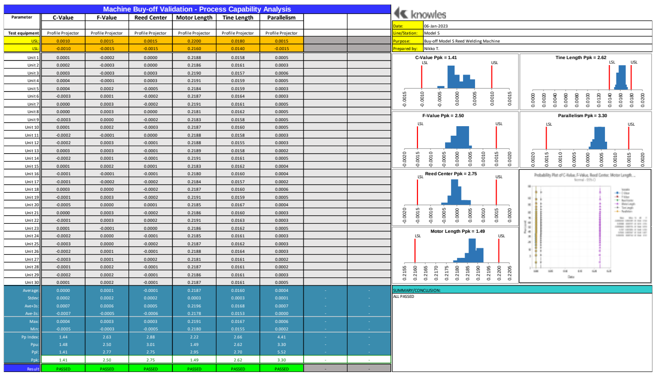


Fig 40: Machine Buy-off Result of Reed Welding Fixture

10.2.11 Man: Bad Judgement

The operators in Model S passed MSA GR&R (Figure 41) with a 2.84% Gage R&R which is lower than the set standard of 10% and an NDC of 49 which is higher than the set standard of 5, thus, the operator can properly judge the defects and not a valid root cause of Failed Adjust (FA) rejection.

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.02948	0.17686	2.84
Repeatability	0.02948	0.17686	2.84
Reproducibility	0.00000	0.00000	0.00
OP ID	0.00000	0.00000	0.00
Part-To-Part	1.03769	6.22616	99.96
Total Variation	1.03811	6.22867	100.00

Number of Distinct Categories = 49

Fig 41: Gage R&R Result of Operator in Reed Welding Process

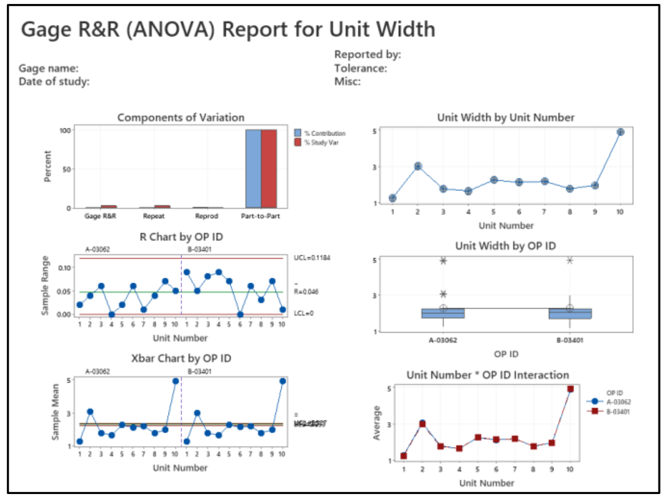


Fig 42: Gage R&R (ANOVA) Report for Unit Width

10.2.12 Material: Diaphragm Forming Issue

The Paired T-Test (Figure 43) resulted in a P-Value of 0.692, which is higher than the set alpha level of 0.05, thus, the test result failed to reject the Null Hypothesis (H_o) and confirmed that the Diaphragm Height does not change after re-forming and not a valid root cause of Failed Adjust (FA) rejection.

Paired T-Test and CI: Before Forming, After Forming

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Before Forming	29	0.106204	0.002970	0.000552
After Forming	29	0.106166	0.002998	0.000557

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.000038	0.000512	0.000095	(-0.000157, 0.000233)

μ_difference: population mean of (Before Forming - After Forming)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
0.40	0.692

Fig 43: Paired T-Test Result of Diaphragm Height