OVERCOMING THE LIMITATIONS OF ACRYLATE-TYPE UV-CURED ADHESIVES UNDER ELEVATED ENVIRONMENTAL AND USE CONDITIONS

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ABSTRACT

The balanced armature driver plays a vital role in the audio products into which it is integrated. Product reliability is fundamental to customer satisfaction, making seamless installation a key consideration. From the customer's perspective, and within the context of reliability, the balanced armature driver's mounting efficiency within the system-level assembly is a critical first step toward ensuring its long-term performance and durability.

This paper tackles the challenges associated with utilizing acrylate-type UV-cured adhesives at the balanced armature driver's terminal tab-to-case interface, particularly under high humidity, elevated temperatures, and exposure to solder flux. In response to the reliability concerns brought about by the inherent material characteristics, Knowles Electronics Philippines fully understood the limitations of the existing UV-cured adhesives and then applied the DMAIC methodology to mitigate the risk.

Within a constrained timeframe, the team understood the impact of these limitations on the customer, successfully contained the issue, identified the root causes, optimized the process, and introduced product improvements to maintain production continuity and support the customer's assembly operations.

1.0 INTRODUCTION

1.1 Background of the Study

BA drivers convert electrical audio signals into mechanical wave energy through electromagnetic induction [1]. A vibrating reed (armature) suspended between two magnets transfers motion via a drive rod to an aluminum diaphragm, generating sound waves.

Widely used in hearing aids, in-ear monitors, and compact audio devices, BA drivers require precise soldering for electrical integration. Most Knowles-manufactured BA drivers are shipped in bare form, necessitating resoldering of the terminal tab to the system-level circuit. Figure 1 illustrates a cross-sectional view of a standard BA driver and its applications.

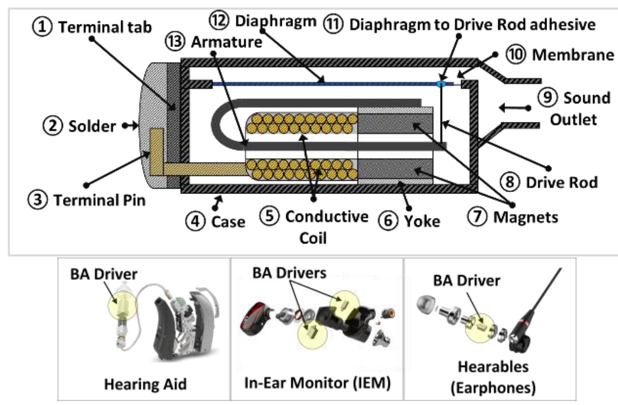

Fig. 1. Cross-section of a standard Balanced Armature driver and typical applications – Hearing Aids, In-Ear Monitors (IEM), and Earphones.

The BA driver, with its compact dimensions of only 5mm x 3mm x 2mm (L x W x T), is an attractive choice for hearable manufacturers seeking to minimize package size while maintaining high-performance audio output. However, its small form factor necessitates a high-precision installation through soldering to avoid compromising electrical connectivity, mechanical stability, and overall acoustic performance.

1.2 DMAIC- Define Phase

1.2.1 Statement of the Problem

An OEM customer of Knowles Electronics reported a high failure rate in Model Y BA drivers, posing risks of operational disruptions, product launch delays, and recalls, necessitating immediate corrective action to ensure product reliability.

The initial investigation identified manual soldering difficulties as the primary cause, leading to terminal tab detachment and unintended movement during and after soldering. Figure 2 compares defective vs. functional units, highlighting terminal tab misalignment, mechanical instability, and adhesive failure. Although the solder joint remains intact, the terminal tab loses adhesion to the case and exhibits noticeable displacement under mechanical force.

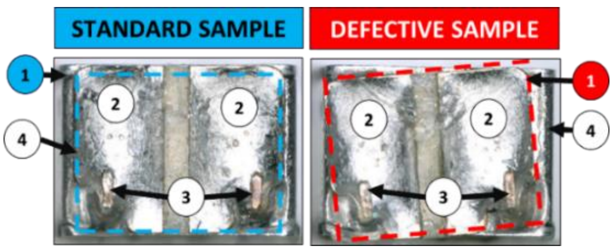

Fig. 2. Standard sample vs Defective unit sample as reported by the customer, images with parts reference to the BA driver cross-section.

1.2.2 Objective of the Study

This study aims to investigate the root causes of terminal tab detachment in Model Y BA drivers during the manual soldering process, as reported by an OEM customer. A key focus is the performance limitations of the acrylate-type UV-cured adhesives used in the terminal tab-to-case interface, particularly under high humidity, elevated temperatures, and solder flux exposure.

Utilizing the DMAIC methodology, this study will characterize failure mechanisms, identify root causes, implement process improvements, and introduce product modifications. By systematically addressing these challenges, the study aims to enhance product durability, ensure operational continuity, and improve customer satisfaction.

1.2.3 Scope and Delimitations of the Study

This study focuses on the strategic adaptation of product parameters and the optimization of the process design to address the inherent limitations of acrylate-type UV-cured adhesives.

2.0 REVIEW OF RELATED WORK

UV-cured adhesives are highly favored in high-speed manufacturing environments due to their rapid polymerization, enabling fast curing and minimal processing time. These properties make them well-suited for both fully automated and semi-automated production lines, where efficiency and throughput are critical [2]. However, acrylate-based UV-cured adhesives exhibit certain limitations, particularly poor humidity reliability as noted by C. Chen et al. [3], and challenges in thermal stability as highlighted by M. Bankaitis et al. [4].

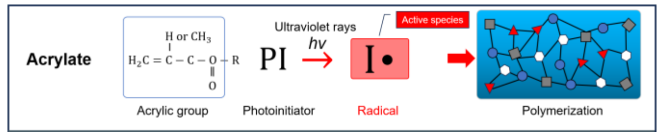

Fig. 3. Free Radical Polymerization of acrylate-based adhesives.

Figure 3 illustrates the mechanism of free radical polymerization in acrylate-based adhesives.

Several sources [5][6][7][8] report that: Free radical polymerization exhibits several disadvantages when exposed to chemicals, high humidity, and elevated temperatures. These conditions can worsen inherent limitations of the process and lead to structural and stability issues in the resulting polymers.

Reduced Radical Stability: High humidity shortens the lifespan of free radicals, which are critical for initiating and propagating polymerization. Moisture can quench radicals prematurely, leading to incomplete monomer conversion and reduced polymer molecular weight. Elevated temperatures may accelerate radical decomposition, further destabilizing the reaction. Increased Chain Transfer Reactions: At higher temperatures, chain transfer to solvents, monomers, or water (introduced by humidity) becomes more prevalent. Hydrolytic Degradation and Structural Instability: Humidity-induced water absorption is particularly problematic for hydrophilic polymers. Accelerated Aging and Oxidation: Combined heat and humidity accelerate oxidative degradation.

These challenges can significantly impact the long-term durability of BA Drivers utilizing acrylate-based UV-cured adhesives, necessitating product and process design optimization to mitigate performance deficiencies.

3.0 METHODOLOGY

3.1 DMAIC – Measure Phase

3.1.1 Customer Failure Rate

To quantify the issue, the customer has reported a failure rate of 28% across affected batches, equating to 246 defective units out of the 868 processed. The units were traced back to Knowles' production from weeks 14, 17, and 20, 2024. A total of 50 units, were shipped back to Knowles for analysis.

3.2 DMAIC – Analyze Phase

3.2.1. Failure Analysis of Returned Samples and Failure Mechanism Identification

Failure analysis of the customer-returned units validated the customer's initial findings, confirming noticeable misalignment between the terminal tab and the case, along with the observable movement of the terminal tab under applied force. The investigation further identified the presence of a liquid substance at the interface between the terminal tab and the case, which is hypothesized to be flux, based on its physical properties, while the adhesive intended to bond these components was no longer detectable.

All returned units failed Knowles' electroacoustic testing, confirming a functional degradation linked to loss of adhesive integrity. In contrast, a standard, non-defective unit exhibited no signs of the liquid substance, and the adhesive remained intact. Refer to Figure 4 for a sample comparison.

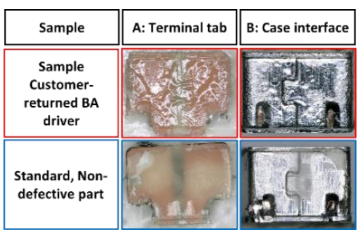

Fig. 4. Standard sample vs Defective unit sample terminal tab to case interface comparison.

3.2.2 Root Cause Identification

3.2.2.1 Balance Armature Driver Product Design and Reliability Requirements.

In this BA Driver model, the terminal tab is bonded to the case using a thin layer of acrylate-type UV-cured adhesive, which is also used to seal the terminal pin hole connecting the coil to the tab. This bond must endure elevated temperatures and solder flux exposure during initial and secondary soldering processes, as well as resist high humidity during storage and use. See Figure 5 for detailed views of the terminal tab-to-case interface design.

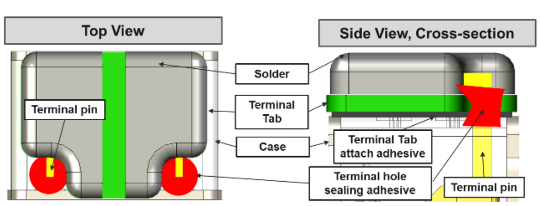

Fig. 5. Top View and Cross-section side view of the BA Driver terminal tab to case interface.

3.2.2.2 Process Mapping and Process Design Review

A thorough understanding and process mapping of the current process design and step-by-step assembly procedure for this BA driver model is essential in identifying factors contributing to the observed failure mechanism.

Given the high-volume, fast-turnaround nature of its partially automated production line, the use of a fast-curing adhesive is necessary to maintain efficiency and throughput. Figure 6 presents the process flow.

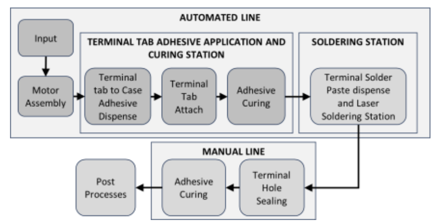

Fig. 6. Process Flow with emphasis on the terminal tab to case assembly, soldering, and terminal hole sealing.

Figure 7 illustrates the step-by-step assembly procedure. The process begins with the application of a single dot of acrylate-based UV-cured adhesive onto the case. The terminal tab is then positioned and pressed onto the adhesive, ensuring even distribution before undergoing UV curing. Following this, the BA driver advances to the next station for solder paste dispensing and laser soldering. These processes are fully automated. Once completed, the BA driver is unloaded from the equipment, and the terminal hole is sealed using the same UV-cured acrylate adhesive at the manual line.

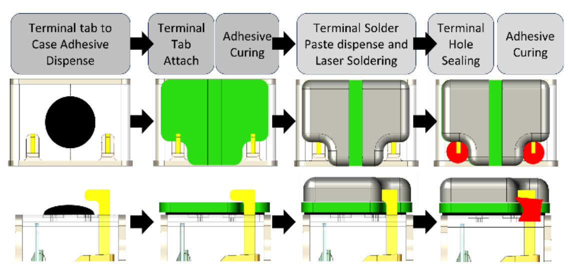

Fig. 7. Process Flow with emphasis on the terminal tab to case assembly, soldering, and terminal hole sealing.

3.2.2.3 Factor Identification and Validation

3.2.2.3.1 Ishikawa Diagram

The Ishikawa diagram, shown in Figure 8, systematically analyzes various potential factors contributing to the detached terminal tab.

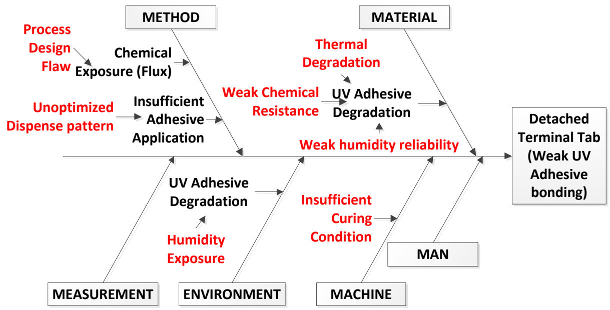

Fig. 8. Ishikawa Diagram for Detached Terminal Tab.

Method: Several process-related deficiencies were hypothesized to contribute to weak bonding and hinder adhesion reliability, including flux exposure, attributed to process design flaws and insufficient adhesive application resulting from an unoptimized terminal tab adhesive dispense pattern. Material: The adhesive's limitations are highlighted in terms of thermal degradation, weak humidity reliability, and weak chemical resistance. These suggest that the material itself may not be well-suited for prolonged exposure to extreme environmental conditions. Machine: Insufficient curing conditions, which implies that improper UV exposure parameters may lead to incomplete polymerization, reducing bonding effectiveness. Environment: Influences, particularly exposure to humidity, further worsen bonding weaknesses.

3.2.2.3.2 Factor Validation

3.2.2.3.2.1 Thermal Degradation and Curing Condition

To assess the validity and extent of terminal tab adhesive degradation caused by exposure to elevated temperatures during soldering, shear testing was conducted on BA driver terminal tabs. The evaluation compared units collected immediately after UV adhesive curing with units that had undergone the terminal tab auto-soldering process. Additionally, shear testing was performed on the remaining BA drivers returned by the customer to further analyze adhesive performance under real-use conditions. The sample size is 30 units per group.

3.2.2.3.2.2 Process Design Flaw, Unoptimized Adhesive Dispense Pattern, Weak Chemical Resistance, and Weak Humidity Reliability

Validation of the remaining potential factors was conducted based on the premise that terminal tab failure is driven by the combined effects of these interacting factors identified in the Ishikawa Diagram.

A full-factorial Design of Experiment (DOE) was conducted to validate the combined effects of insufficient curing, adhesive bond weakening from flux exposure due to process design flaws, inadequate adhesive application, and high humidity exposure. As illustrated in Figure 9, the DOE input variables included adhesive dispense pattern, process design, and 1-hour humidity exposure at 95% RH—chosen to simulate the customer's field conditions and time when failures occurred based on the Peck Reliability Model. The output responses targeted minimizing flux presence and terminal tab movement under an applied force.

Input Variables	Levels	Output Variables	Levels	Target
Adhesive Dispense Pattern	2 Levels (Single dot minimum settings,3-dot optimized pattern)	Flux Presence	2 levels (1- with the presence of flux, 0- without the presence of flux)	minimize
Process Design	2 Levels (Terminal hole sealing prior Auto Soldering, Auto Soldering prior Terminal hole sealing)	Movement of the Terminal tab under applied force	2 levels (1- with observable movement of the terminal tab, 0- without observable movement of the terminal tab)	minimize
Exposure to Elevated levels of humidity	2 Levels (No Exposure @t=0, 1 week Exposure to high Humidity @95%)			

Fig. 9. Key Process Input and Output Variables.

Flux Ingress hypothesis: Figure 10 presents the hypothesis that flux penetrates beneath the terminal tab during the soldering process through capillary action along the terminal pin. The adhesive dispense pattern (targeted minimum amount) may contribute to increased flux accumulation as the void space that the adhesive should have occupied becomes susceptible to flux infiltration.

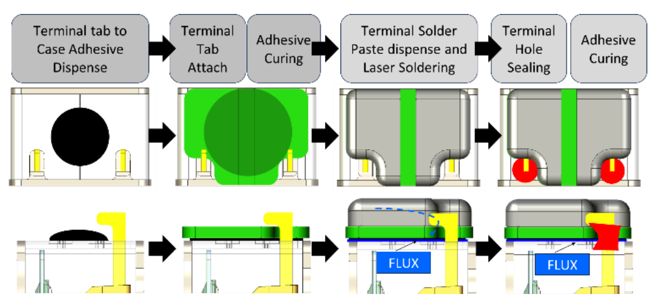

Fig. 10. Illustration of flux ingress hypothesis.

A 3-dot dispense pattern was introduced as the second level of the dispense pattern factor. This adjustment is based on the premise that it improves coverage and offers excellent resilience to variations in dispensed amounts. Additionally, reordering the terminal laser and terminal hole sealing processes is expected to disrupt the flux capillary action, effectively blocking flux ingress through the terminal hole and preventing adhesive failure. See Figure 11.

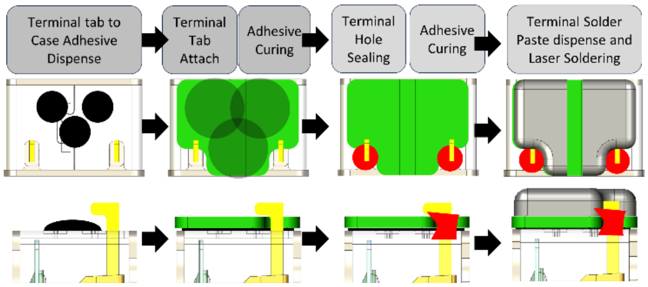

Fig. 11. Illustration of 3-dot dispense pattern and re-order of process flow with terminal hole sealing preceding the terminal tab soldering.

4.0 RESULTS AND DISCUSSION

4.1 DMAIC – Analyze Phase (Results)

4.1.1 Shear Test Results (Thermal Degradation and Curing Condition)

The ANOVA results, with a Welch's test (not assuming equal variances) P-value of 0.000, confirm a statistically significant difference in the mean shear strength between the three groups of samples. The boxplot in Figure 12 illustrates this trend, showing that while auto-soldering leads to a reduction in terminal tab-to-case shear strength, this decrease is less pronounced compared to the shear strength observed in the customer-returned samples, indicating additional factors contributing to the failures. See Appendix A for the full statistical analysis.

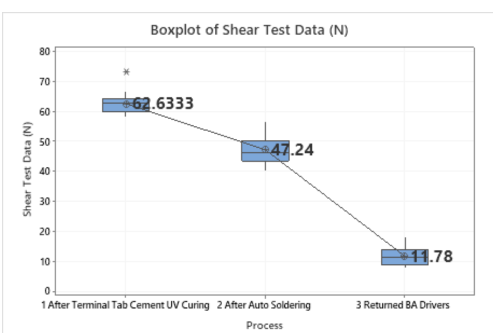

Fig. 12. Boxplot of the Terminal tab-to-case shear strength comparison of the samples immediately taken after the UV curing process vs. samples subjected to the soldering process vs the returned BA drivers from the customer.

The visual condition of the samples after the UV curing process was also visually inspected, confirming a full curing of the adhesive. See Figure 13.

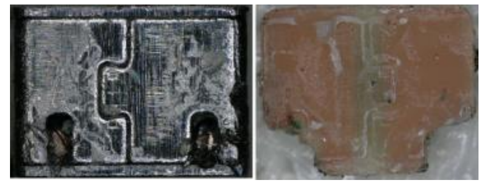

Fig. 13. Sample images of BA Drivers achieving full curing conditions.

4.1.2 DOE Results

4.1.2.1 Flux Presence

The ANOVA results show that adhesive dispense pattern and process design significantly affect flux presence (P = 0.000), while exposure has no significant impact (P = 0.711). Among two-way interactions, only the adhesive dispense pattern × process design is significant (P = 0.000). The three-way interaction is not significant (P = 0.458). The model explains 51.71% of the variance, indicating moderate explanatory power.

Main effects and interaction plots indicate that the 3-dot dispense pattern and a process sequence with terminal hole sealing preceding auto terminal tab soldering each reduce flux presence, but their combination further lowers flux levels. Flux presence remains independent of exposure to high humidity. See Appendices B and D for detailed data.

4.1.2.2 Terminal Tab movement:

The ANOVA results show that adhesive dispense pattern, process design, and exposure each significantly affect terminal tab movement (P ≤ 0.000). Among two-way interactions, only process design × exposure is not significant (P = 0.163), while all others remain significant (P = 0.000). The three-way interaction (adhesive dispense pattern × process design × exposure) is also not significant (P = 0.063). The model explains 42.05% of the variance, indicating moderate predictive power.

Main effects and interaction plots reveal that the 3-dot dispense pattern, a process sequence with terminal hole sealing preceding auto terminal tab soldering, and no humidity exposure effectively minimize terminal tab movement. Notably, adopting the 3-dot dispense pattern alone significantly reduces movement regardless of process design or humidity exposure. Detailed statistics are in Appendices C and E.

4.1.2.3 Response Optimization: Flux & Terminal Tab Movement

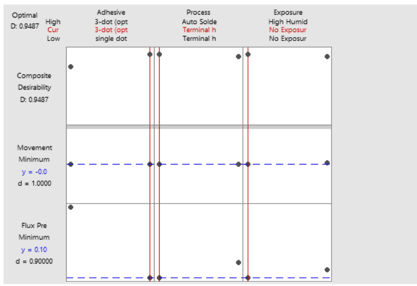

Fig. 14. Response Optimization and Composite Desirability Results.

DOE results show that using a 3-dot adhesive dispense pattern combined with sealing the terminal hole before soldering the terminal tab minimizes flux presence and tab movement, achieving a composite desirability of 0.9487 (Figure 14). This confirms that the previous single-dot pattern and soldering the tab before sealing contributed to customer-reported failures, which were worsened by high humidity exposure. Refer to Appendix F for additional desirability scenarios.

4.1.2.4 Correlation of Flux Presence to Terminal Tab Movement Output Responses

Pairwise Pearson Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Movement of Terminal Tab	Flux Presence	120	0.247	(0.071, 0.408)	0.007

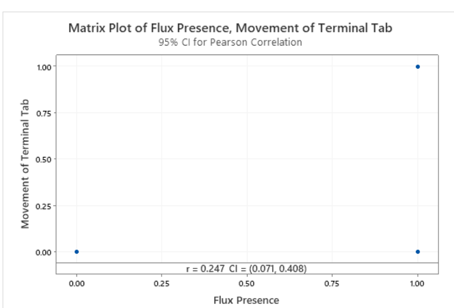

Fig. 15. Correlation results of Flux presence to the terminal tab movement.

The Pearson correlation analysis of the two output responses in the DOE—flux presence and terminal tab movement, excluding the exposure to humidity factor—reveals a statistically significant relationship, as indicated by a P-value of 0.007 (< α = 0.005). These results confirm a direct association between flux presence and terminal tab movement, reinforcing the impact of flux on mechanical stability. See Figure 15.

4.1.3 Factor Validation Summary

Figure 16 outlines the valid and invalid factors contributing to terminal tab detachment. The analysis confirms that flux exposure, resulting from process design flaws and insufficient adhesive coverage due to an unoptimized dispense pattern, significantly compromises bond integrity. Additionally, exposure to elevated temperatures during Terminal Tab Auto Soldering weakens the initial adhesive bond strength, accelerating degradation. Humidity exposure further amplifies adhesive instability, acting as a secondary degradation factor that worsens pre-existing weaknesses.

Factor	Hypothesis	Results
Thermal Degradation	Exposure to elevated temperatures during Terminal tab Auto Soldering degrades the adhesive bonding.	Valid
Process design flaw	Flux exposure, attributed to process design flaws and insufficient adhesive application resulting from an unoptimized terminal tab adhesive dispense pattern contributes to weak adhesive bonding.	Valid
Unoptimized adhesive dispense pattern		Valid
Weak Chemical Resistance		Valid
Humidity exposure, Weak humidity reliability	Exposure to humidity, further exacerbates bonding weaknesses.	Valid
Insufficient curing condition	Insufficient curing conditions may lead to incomplete polymerization	Invalid

Fig. 16. Factor Validation Results.

4.2 DMAIC – Improve Phase

The Knowles team acknowledges the necessity of process enhancements and has implemented process sequence optimization and adhesive dispense pattern refinement to effectively mitigate flux contamination. The revised process flow, outlined in Figure 17, introduces a critical sequence modification - terminal hole sealing now precedes terminal tab auto-soldering - ensuring improved bonding integrity and reliability. A subsequent qualification of BA Drivers manufactured under the optimized process confirmed the effectiveness of these refinements, yielding successful validation results.

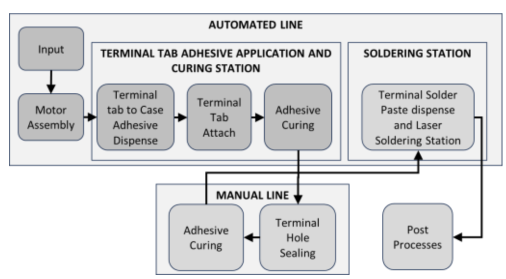

Fig. 17. Optimized Process Flow.

While these immediate adjustments sufficiently address adhesion performance issues to satisfy the customer's needs, mitigating thermal degradation and humidity-related weaknesses requires a material upgrade to the existing acrylate-based UV-cured adhesive.

4.3 DMAIC – Control Phase

All relevant documents impacted by the change—including the Process Flow, PFMEA, Control Plan, SPC Sampling Plan, and Product Specifications—were updated accordingly. Corresponding Process Change Notifications (PCNs) were submitted to the OEM customer for approval before implementation. To ensure sustained performance and process reliability, Key Performance Indicators (KPIs) were continuously monitored. Notably, the new batch of BA Drivers shipped recorded zero customer complaints and no recurrence of previous issues.

5.0 CONCLUSION

Terminal tab detachment in Model Y BA drivers is attributed to flux contamination due to process design flaws, and inadequate adhesive application, amplifying the inherent limitations of acrylate-based UV-cured adhesives—particularly their susceptibility to thermal degradation and environmental instability. Optimizing the adhesive dispense pattern and refining process sequencing were identified as effective solutions to minimize flux ingress and enhance terminal tab stability. However, addressing the material limitations of acrylate-based adhesives remains crucial for long-term reliability, necessitating further material optimization beyond process improvements.

6.0 RECOMMENDATIONS

Knowles is actively pursuing an alternative terminal tab attach UV-cured adhesive, aiming to strengthen long-term adhesive stability under high-temperature exposure.

7.0 ACKNOWLEDGMENT

The authors would like to thank Knowles Electronics Philippines, its management team, and those who were involved in the project.

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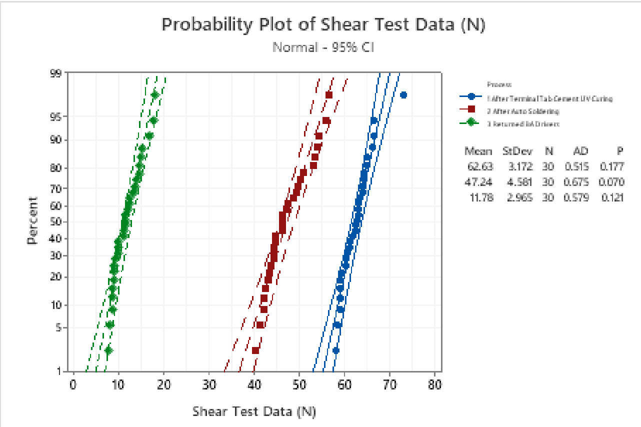
9.0 ABOUT THE AUTHORS

Dominic John P. Patarata, a licensed Electronics Engineer and certified Six Sigma Green Belt, is Six Sigma Black Belt trained and pursuing certification. He served as a Quality Engineer at Cebu Mitsumi Inc. for four years and has been a Sr. Quality Engineer at Knowles Electronics (Philippines) Corporation for a decade. He earned recognition at the 2023 ASEMEP Symposium, securing 2nd Runner-up for Best Paper and Best Presenter in FA/Reliability. In 2024, he won 1st Runner-up for Best Paper in the Product Track for his study on UV-cured adhesives for drive rod bonding.

Butch Angelo A. Aglibot, a licensed Electronics Engineer and Six Sigma Green Belt practitioner, graduated from Cebu Institute of Technology University. He served as a Quality Engineer at Taiyo Yuden Phils. Inc – Cebu for 12 years and has been with Knowles Electronics (Philippines) Corporation for 3 years. He co-authored the 2024 ASEMEP Product Track 1st Runner-up study on UV-cured adhesives for optimized drive rod bonding.

10.0 APPENDIX

Appendix A– One-way ANOVA results: Shear Test Data (N) versus Process



Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were not assumed for the analysis.

Factor Information

Factor	Levels	Values
Process	3	1 After Terminal Tab Cement UV Curing, 2 After Auto Soldering, 3 Returned BA Drivers

Welch's Test

Source	DF Num	DF Den	F-Value	P-Value
Process	2	56.4946	2113.07	0.000

Model Summary

R-sq	R-sq(adj)	R-sq(pred)
97.25%	97.18%	97.05%

Means

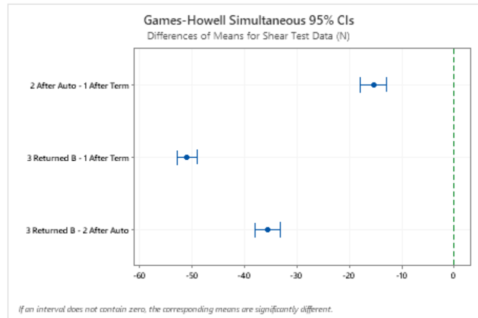
Process	N	Mean	StDev	95% CI
1 After Terminal Tab Cement UV Curing	30	62.633	3.172	(61.449, 63.818)
2 After Auto Soldering	30	47.240	4.581	(45.530, 48.950)
3 Returned BA Drivers	30	11.780	2.965	(10.673, 12.887)

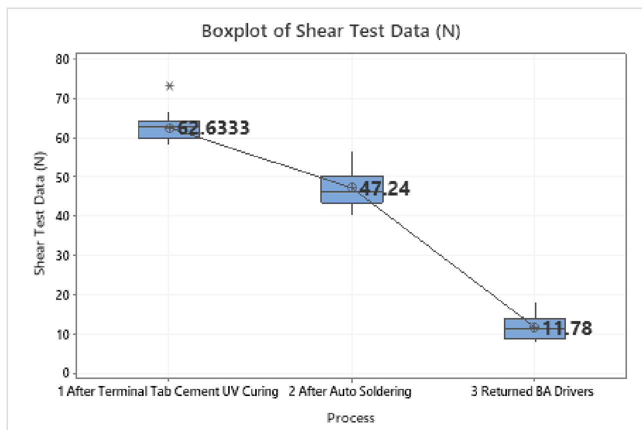
Games-Howell Pairwise Comparisons

Grouping Information Using the Games-Howell Method and 95% Confidence

Process	N	Mean	Grouping		
1 After Terminal Tab Cement UV Curing	30	62.633	A		
2 After Auto Soldering	30	47.240		B	
3 Returned BA Drivers	30	11.780			C

Means that do not share a letter are significantly different.





Appendix B– General Factorial Regression: Flux Presence versus Adhesive Dispense Pattern, Process Design, Exposure

Factor Information

Factor	Levels	Values
Adhesive dispense pattern	2	single dot (minimum settings), 3-dot (optimized settings)
Process Design	2	Terminal hole sealing prior Auto Soldering, Auto Soldering prior Terminal hole sealing
Exposure	2	No Exposure, High Humidity

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	29.9833	4.2833	35.49	0.000
Linear	3	24.4333	8.1444	67.48	0.000
Adhesive dispense pattern	1	17.0667	17.0667	141.41	0.000
Process Design	1	7.3500	7.3500	60.90	0.000
Exposure	1	0.0167	0.0167	0.14	0.711
2-Way Interactions	3	5.4833	1.8278	15.14	0.000
Adhesive dispense pattern*Process Design	1	5.4000	5.4000	44.74	0.000
Adhesive dispense pattern*Exposure	1	0.0667	0.0667	0.55	0.458
Process Design*Exposure	1	0.0167	0.0167	0.14	0.711
3-Way Interactions	1	0.0667	0.0667	0.55	0.458
Adhesive dispense pattern*Process Design*Exposure	1	0.0667	0.0667	0.55	0.458
Error	232	28.0000	0.1207		
Total	239	57.9833			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.347404	51.71%	50.25%	48.32%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.4083	0.0224	18.21	0.000	
Adhesive dispense pattern					
single dot (minimum settings)	0.2667	0.0224	11.89	0.000	1.00
Process Design					
Terminal hole sealing prior Auto Soldering	-0.1750	0.0224	-7.80	0.000	1.00
Exposure					
No Exposure	0.0083	0.0224	0.37	0.711	1.00
Adhesive dispense pattern*Process Design					
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	-0.1500	0.0224	-6.69	0.000	1.00
Adhesive dispense pattern*Exposure					
single dot (minimum settings) No Exposure	0.0167	0.0224	0.74	0.458	1.00
Process Design*Exposure					
Terminal hole sealing prior Auto Soldering No Exposure	0.0083	0.0224	0.37	0.711	1.00
Adhesive dispense pattern*Process Design*Exposure					
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	0.0167	0.0224	0.74	0.458	1.00

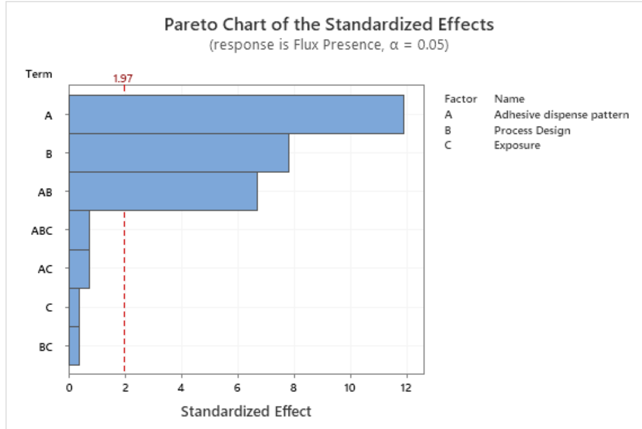
Regression Equation

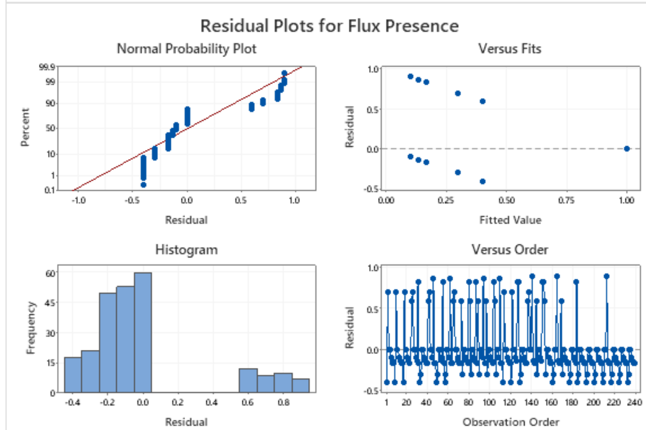
Flux Presence = 0.4083 + 0.2667 Adhesive dispense pattern_single dot (minimum settings)
- 0.2667 Adhesive dispense pattern_3-dot (optimized settings)
- 0.1750 Process Design_Terminal hole sealing prior Auto Soldering
+ 0.1750 Process Design_Auto Soldering prior Terminal hole sealing
+ 0.0083 Exposure_No Exposure - 0.0083 Exposure_High Humidity
- 0.1500 Adhesive dispense pattern*Process Design_single dot (minimum settings) Terminal hole sealing prior Auto Soldering
+ 0.1500 Adhesive dispense pattern*Process Design_single dot (minimum settings) Auto Soldering prior Terminal hole sealing
+ 0.1500 Adhesive dispense pattern*Process Design_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering
- 0.1500 Adhesive dispense pattern*Process Design_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing
+ 0.0167 Adhesive dispense pattern*Exposure_single dot (minimum settings) No Exposure - 0.0167 Adhesive dispense pattern*Exposure_single dot (minimum settings) High Humidity - 0.0167 Adhesive dispense pattern*Exposure_3-dot (optimized settings) No Exposure
+ 0.0167 Adhesive dispense pattern*Exposure_3-dot (optimized settings) High Humidity + 0.0083 Process Design*Exposure_Terminal hole sealing prior Auto Soldering No Exposure - 0.0083 Process Design*Exposure_Terminal hole sealing prior Auto Soldering High Humidity - 0.0083 Process Design*Exposure_Auto Soldering prior Terminal hole sealing No Exposure
+ 0.0083 Process Design*Exposure_Auto Soldering prior Terminal hole sealing High Humidity
+ 0.0167 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure
- 0.0167 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Terminal hole sealing prior Auto Soldering High Humidity
- 0.0167 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Auto Soldering prior Terminal hole sealing No Exposure
+ 0.0167 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Auto Soldering prior Terminal hole sealing High Humidity
- 0.0167 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering No Exposure
+ 0.0167 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering High Humidity
+ 0.0167 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing No Exposure
- 0.0167 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing High Humidity

Fits and Diagnostics for Unusual Observations

Obs	Flux Presence	Fit	Resid	Std Resid	
2	1.0000	0.3000	0.7000	2.05	R
10	1.0000	0.3000	0.7000	2.05	R
18	1.0000	0.3000	0.7000	2.05	R
26	1.0000	0.3000	0.7000	2.05	R
31	1.0000	0.1667	0.8333	2.44	R
42	1.0000	0.3000	0.7000	2.05	R
46	1.0000	0.1333	0.8667	2.54	R
55	1.0000	0.1667	0.8333	2.44	R
62	1.0000	0.1333	0.8667	2.54	R
66	1.0000	0.3000	0.7000	2.05	R
80	1.0000	0.1667	0.8333	2.44	R
87	1.0000	0.1667	0.8333	2.44	R
94	1.0000	0.1333	0.8667	2.54	R
104	1.0000	0.1667	0.8333	2.44	R
110	1.0000	0.1333	0.8667	2.54	R
114	1.0000	0.3000	0.7000	2.05	R
122	1.0000	0.3000	0.7000	2.05	R
127	1.0000	0.1667	0.8333	2.44	R
128	1.0000	0.1667	0.8333	2.44	R
138	1.0000	0.3000	0.7000	2.05	R
141	1.0000	0.1000	0.9000	2.63	R
151	1.0000	0.1667	0.8333	2.44	R
152	1.0000	0.1667	0.8333	2.44	R
165	1.0000	0.1000	0.9000	2.63	R
184	1.0000	0.1667	0.8333	2.44	R
213	1.0000	0.1000	0.9000	2.63	R

R Large residual





Appendix C– General Factorial Regression: Movement of Terminal Tab versus Adhesive dispense pattern, Process Design, Exposure

Factor Information

Factor	Levels	Values
Adhesive dispense pattern	2	single dot (minimum settings), 3-dot (optimized settings)
Process Design	2	Terminal hole sealing prior Auto Soldering, Auto Soldering prior Terminal hole sealing
Exposure	2	No Exposure, High Humidity

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value
Model	7	12.8667	1.83810	24.05
Linear	3	8.7000	2.90000	37.94
Adhesive dispense pattern	1	4.8167	4.81667	63.02
Process Design	1	1.0667	1.06667	13.95
Exposure	1	2.8167	2.81667	36.85
2-Way Interactions	3	3.9000	1.30000	17.01
Adhesive dispense pattern*Process Design	1	1.3500	1.35000	17.66
Adhesive dispense pattern*Exposure	1	2.4000	2.40000	31.40
Process Design*Exposure	1	0.1500	0.15000	1.96
3-Way Interactions	1	0.2667	0.26667	3.49
Adhesive dispense pattern*Process Design*Exposure	1	0.2667	0.26667	3.49
Error	232	17.7333	0.07644	
Total	239	30.6000		

Source	P-Value
Model	0.000
Linear	0.000
Adhesive dispense pattern	0.000
Process Design	0.000
Exposure	0.000
2-Way Interactions	0.000
Adhesive dispense pattern*Process Design	0.000
Adhesive dispense pattern*Exposure	0.000
Process Design*Exposure	0.163
3-Way Interactions	0.063
Adhesive dispense pattern*Process Design*Exposure	0.063
Error	
Total	

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.276472	42.05%	40.30%	37.98%

Coefficients

Term	Coef
Constant	0.1500
Adhesive dispense pattern	
single dot (minimum settings)	0.1417
Process Design	
Terminal hole sealing prior Auto Soldering	-0.0667
Exposure	
No Exposure	-0.1083
Adhesive dispense pattern*Process Design	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	-0.0750
Adhesive dispense pattern*Exposure	
single dot (minimum settings) No Exposure	-0.1000
Process Design*Exposure	
Terminal hole sealing prior Auto Soldering No Exposure	0.0250
Adhesive dispense pattern*Process Design*Exposure	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	0.0333

Term	SE Coef
Constant	0.0178
Adhesive dispense pattern	
single dot (minimum settings)	0.0178
Process Design	
Terminal hole sealing prior Auto Soldering	0.0178
Exposure	
No Exposure	0.0178
Adhesive dispense pattern*Process Design	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	0.0178
Adhesive dispense pattern*Exposure	
single dot (minimum settings) No Exposure	0.0178
Process Design*Exposure	
Terminal hole sealing prior Auto Soldering No Exposure	0.0178
Adhesive dispense pattern*Process Design*Exposure	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	0.0178

Term	T-Value
Constant	8.41
Adhesive dispense pattern	
single dot (minimum settings)	7.94
Process Design	
Terminal hole sealing prior Auto Soldering	-3.74
Exposure	
No Exposure	-6.07
Adhesive dispense pattern*Process Design	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	-4.20
Adhesive dispense pattern*Exposure	
single dot (minimum settings) No Exposure	-5.60
Process Design*Exposure	
Terminal hole sealing prior Auto Soldering No Exposure	1.40
Adhesive dispense pattern*Process Design*Exposure	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	1.87

Term	P-Value
Constant	0.000
Adhesive dispense pattern	
single dot (minimum settings)	0.000
Process Design	
Terminal hole sealing prior Auto Soldering	0.000
Exposure	
No Exposure	0.000
Adhesive dispense pattern*Process Design	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	0.000
Adhesive dispense pattern*Exposure	
single dot (minimum settings) No Exposure	0.000
Process Design*Exposure	
Terminal hole sealing prior Auto Soldering No Exposure	0.163
Adhesive dispense pattern*Process Design*Exposure	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	0.063

Term	VIF
Constant	
Adhesive dispense pattern	
single dot (minimum settings)	1.00
Process Design	
Terminal hole sealing prior Auto Soldering	1.00
Exposure	
No Exposure	1.00
Adhesive dispense pattern*Process Design	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering	1.00
Adhesive dispense pattern*Exposure	
single dot (minimum settings) No Exposure	1.00
Process Design*Exposure	
Terminal hole sealing prior Auto Soldering No Exposure	1.00
Adhesive dispense pattern*Process Design*Exposure	
single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure	1.00

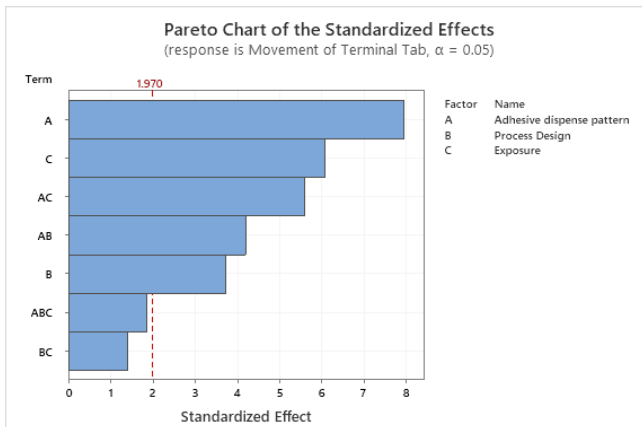
Regression Equation

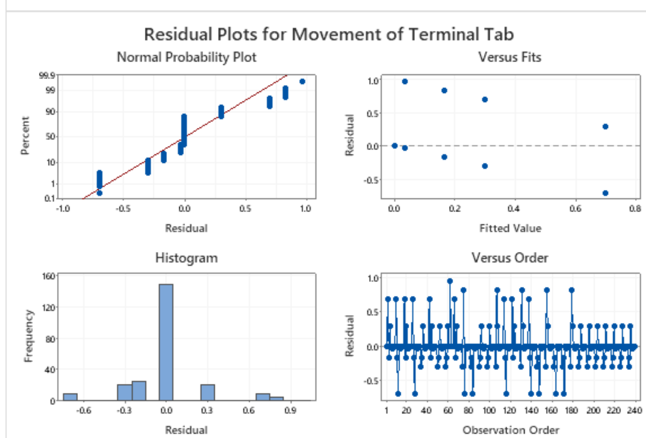
Movement of Terminal Tab = 0.1500 + 0.1417 Adhesive dispense pattern_single dot (minimum settings) - 0.1417 Adhesive dispense pattern_3-dot (optimized settings) - 0.0667 Process Design_Terminal hole sealing prior Auto Soldering + 0.0667 Process Design_Auto Soldering prior Terminal hole sealing - 0.1083 Exposure_No Exposure + 0.1083 Exposure_High Humidity - 0.0750 Adhesive dispense pattern*Process Design_single dot (minimum settings) Terminal hole sealing prior Auto Soldering + 0.0750 Adhesive dispense pattern*Process Design_single dot (minimum settings) Auto Soldering prior Terminal hole sealing + 0.0750 Adhesive dispense pattern*Process Design_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering - 0.0750 Adhesive dispense pattern*Process Design_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing - 0.1000 Adhesive dispense pattern*Exposure_single dot (minimum settings) No Exposure + 0.1000 Adhesive dispense pattern*Exposure_single dot (minimum settings) High Humidity + 0.1000 Adhesive dispense pattern*Exposure_3-dot (optimized settings) No Exposure - 0.1000 Adhesive dispense pattern*Exposure_3-dot (optimized settings) High Humidity + 0.0250 Process Design*Exposure_Terminal hole sealing prior Auto Soldering No Exposure - 0.0250 Process Design*Exposure_Terminal hole sealing prior Auto Soldering High Humidity - 0.0250 Process Design*Exposure_Auto Soldering prior Terminal hole sealing No Exposure + 0.0250 Process Design*Exposure_Auto Soldering prior Terminal hole sealing High Humidity + 0.0333 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Terminal hole sealing prior Auto Soldering No Exposure - 0.0333 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Terminal hole sealing prior Auto Soldering High Humidity - 0.0333 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Auto Soldering prior Terminal hole sealing No Exposure + 0.0333 Adhesive dispense pattern*Process Design*Exposure_single dot (minimum settings) Auto Soldering prior Terminal hole sealing High Humidity - 0.0333 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering No Exposure + 0.0333 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Terminal hole sealing prior Auto Soldering High Humidity + 0.0333 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing No Exposure - 0.0333 Adhesive dispense pattern*Process Design*Exposure_3-dot (optimized settings) Auto Soldering prior Terminal hole sealing High Humidity

Fits and Diagnostics for Unusual Observations

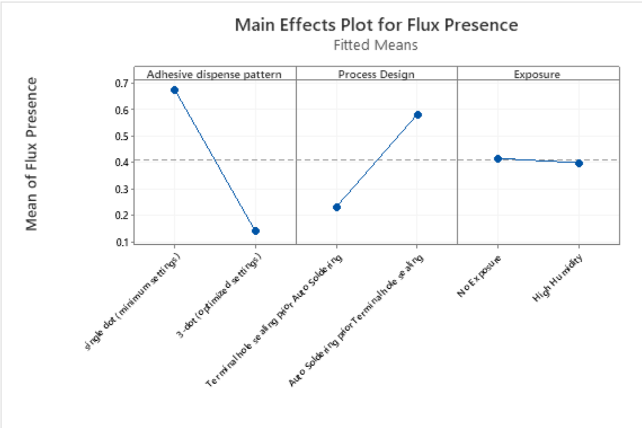
Obs	Movement of Terminal Tab	Fit	Resid	Std Resid	
2	1.0000	0.3000	0.7000	2.58	R
10	1.0000	0.3000	0.7000	2.58	R
12	0.0000	0.7000	-0.7000	-2.58	R
18	1.0000	0.3000	0.7000	2.58	R
26	1.0000	0.3000	0.7000	2.58	R
28	0.0000	0.7000	-0.7000	-2.58	R
42	1.0000	0.3000	0.7000	2.58	R
62	1.0000	0.0333	0.9667	3.56	R
66	1.0000	0.3000	0.7000	2.58	R
75	1.0000	0.1667	0.8333	3.07	R
76	0.0000	0.7000	-0.7000	-2.58	R
84	0.0000	0.7000	-0.7000	-2.58	R
107	1.0000	0.1667	0.8333	3.07	R
114	1.0000	0.3000	0.7000	2.58	R
116	0.0000	0.7000	-0.7000	-2.58	R
122	1.0000	0.3000	0.7000	2.58	R
131	1.0000	0.1667	0.8333	3.07	R
138	1.0000	0.3000	0.7000	2.58	R
140	0.0000	0.7000	-0.7000	-2.58	R
148	0.0000	0.7000	-0.7000	-2.58	R
155	1.0000	0.1667	0.8333	3.07	R
164	0.0000	0.7000	-0.7000	-2.58	R
172	0.0000	0.7000	-0.7000	-2.58	R
179	1.0000	0.1667	0.8333	3.07	R

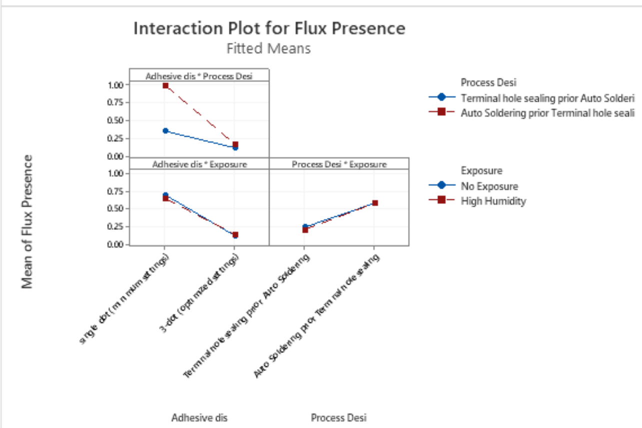
R Large residual



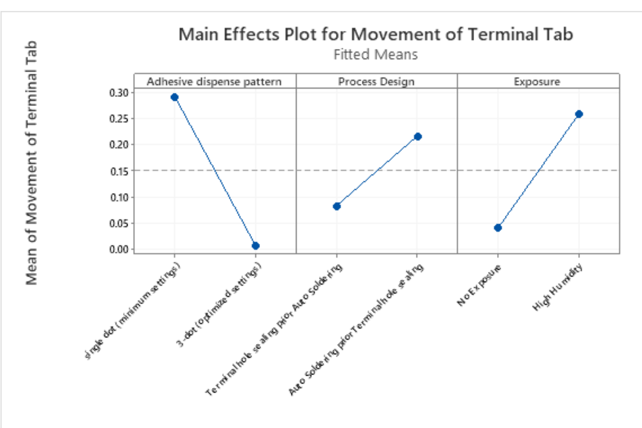


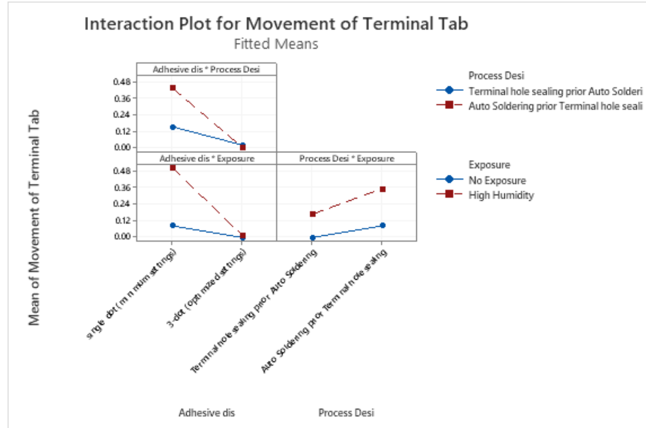
Appendix D– Factorial Plots for Flux Presence





Appendix E– Factorial Plots for Movement of Terminal Tab





Appendix F– Response Optimization and Composite Desirability Results of Movement of Terminal Tab, Flux Presence

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Movement of Terminal Tab	Minimum		0	1	1	1
Flux Presence	Minimum		0	1	1	1

Solution

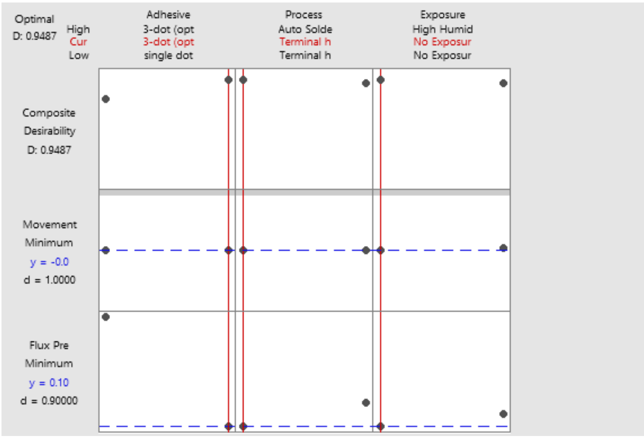
Solution	Adhesive dispense pattern	Process Design	Exposure
1	3-dot (optimized settings)	Terminal hole sealing prior Auto Soldering	No Exposure

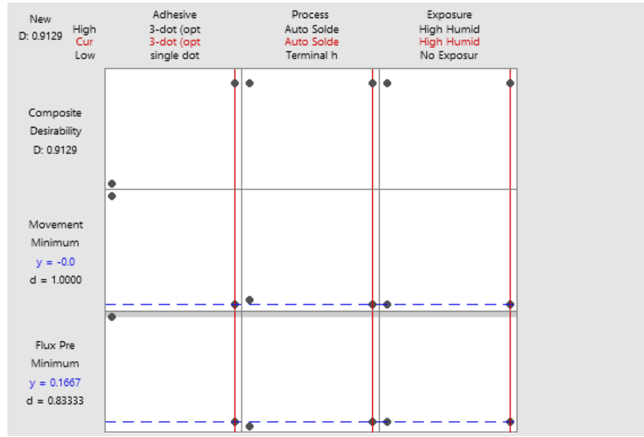
Solution	Movement of Terminal Tab Fit	Flux Presence Fit	Composite Desirability
1	-0.0000000	0.1	0.948683

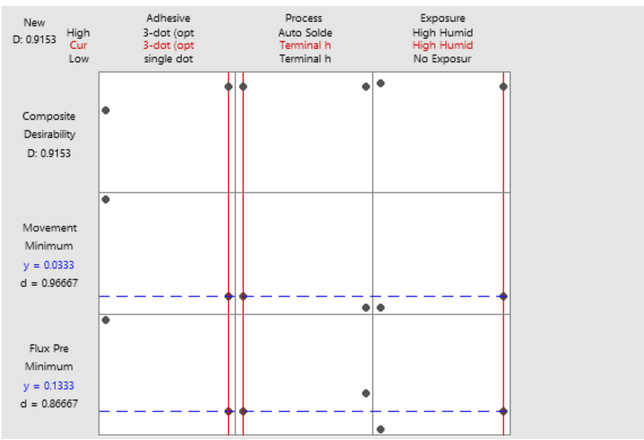
Multiple Response Prediction

Variable	Setting
Adhesive dispense pattern	3-dot (optimized settings)
Process Design	Terminal hole sealing prior Auto Soldering
Exposure	No Exposure

Response	Fit	SE Fit	95% CI	95% PI
Movement of Terminal Tab	-0.0000	0.0505	(-0.0995, 0.0995)	(-0.5537, 0.5537)
Flux Presence	0.1000	0.0634	(-0.0250, 0.2250)	(-0.5958, 0.7958)


Optimal
D: 0.9487
High
Cur
Low
Adhesive
3-dot (opt
3-dot (opt
single dot
Process
Auto Solde
Terminal h
Terminal h
Exposure
High Humid
No Exposur
No Exposur
Composite
Desirability
D: 0.9487
Movement
Minimum
y = -0.0
d = 1.0000
Flux Pre
Minimum
y = 0.10
d = 0.90000


New
D: 0.9129
High
Cur
Low
Adhesive
3-dot (opt
3-dot (opt
single dot
Process
Auto Solde
Auto Solde
Terminal h
Exposure
High Humid
High Humid
No Exposur
Composite
Desirability
D: 0.9129
Movement
Minimum
y = -0.0
d = 1.0000
Flux Pre
Minimum
y = 0.1667
d = 0.83333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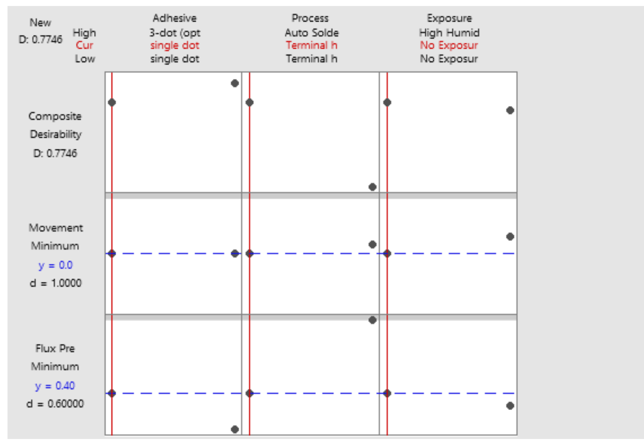
Cur
Low
Adhesive
3-dot (opt
3-dot (opt
single dot
Process
Auto Solde
Terminal h
Terminal h
Exposure
High Humid
High Humid
No Exposur
Composite
Desirability
D: 0.9153
Movement
Minimum
y = 0.0333
d = 0.96667
Flux Pre
Minimum
y = 0.1333
d = 0.86667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D: 0.7746
High
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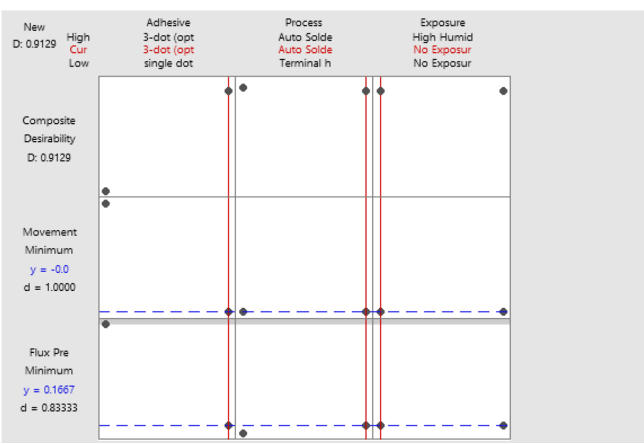
Low
Adhesive
3-dot (opt
single dot
single dot
Process
Auto Solde
Terminal h
Terminal h
Exposure
High Humid
No Exposur
No Exposur
Composite
Desirability
D: 0.7746
Movement
Minimum
y = 0.0
d = 1.0000
Flux Pre
Minimum
y = 0.40
d = 0.60000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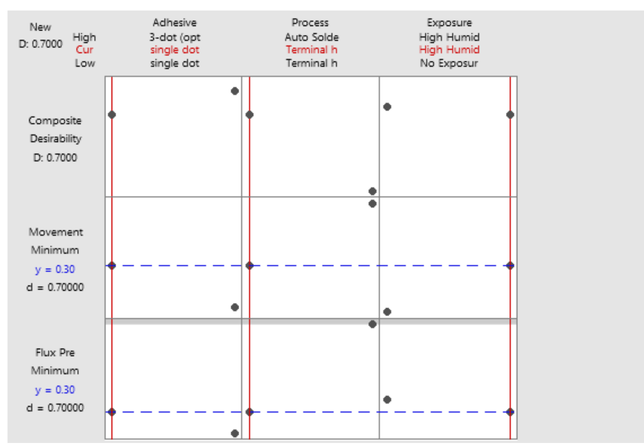
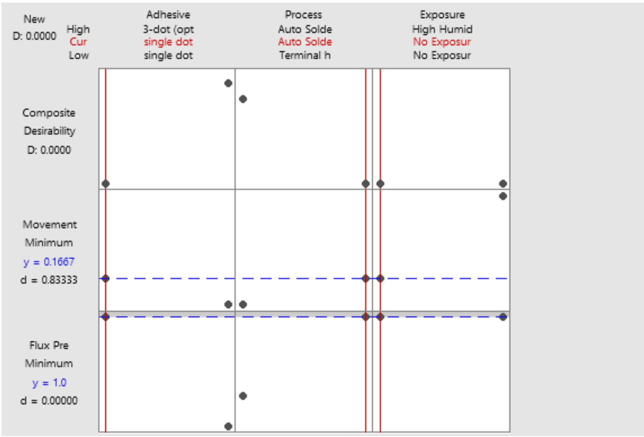
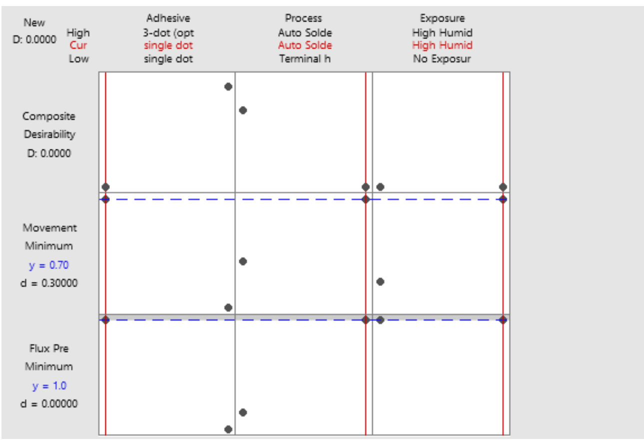
High
Cur
Low
Adhesive
3-dot (opt
3-dot (opt
single dot
Process
Auto Solde
Auto Solde
Terminal h
Exposure
High Humid
No Exposur
No Exposur
Composite
Desirability
D: 0.9129
Movement
Minimum
y = -0.0
d = 1.0000
Flux Pre
Minimum
y = 0.1667
d = 0.83333


New
D: 0.7000
High
Cur
Low
Adhesive
3-dot (opt
single dot
single dot
Process
Auto Solde
Terminal h
Terminal h
Exposure
High Humid
High Humid
No Exposur
Composite
Desirability
D: 0.7000
Movement
Minimum
y = 0.30
d = 0.70000
Flux Pre
Minimum
y = 0.30
d = 0.70000


New
D: 0.0000
High
Cur
Low
Adhesive
3-dot (opt
single dot
single dot
Process
Auto Solde
Auto Solde
Terminal h
Exposure
High Humid
No Exposur
No Exposur
Composite
Desirability
D: 0.0000
Movement
Minimum
y = 0.1667
d = 0.83333
Flux Pre
Minimum
y = 1.0
d = 0.00000


New
D: 0.0000
High
Cur
Low
Adhesive
3-dot (opt
single dot
single dot
Process
Auto Solde
Auto Solde
Terminal h
Exposure
High Humid
High Humid
No Exposur
Composite
Desirability
D: 0.0000
Movement
Minimum
y = 0.70
d = 0.30000
Flux Pre
Minimum
y = 1.0
d = 0.00000