CHEMISTRY SELECTION IN UV-CURED ADHESIVES FOR OPTIMIZED DRIVE ROD BONDING OF BALANCED ARMATURE DRIVERS

Dominic John P. Patarata
Butch Angelo A. Aglibot

Quality Department, MedTech and Specialty Audio
Knowles Electronics (Philippines) Corporation, Cebu Light Industrial Park, Basak, Lapu-Lapu City, Cebu
Dominic.Patarata@Knowles.com
Butch.Aglibot@Knowles.com

ABSTRACT

Material selection is crucial in the design of a balanced armature driver. It plays a pivotal role in ensuring the long-term performance, reliability, and overall success of a particular product or model. The adhesive that connects the drive rod to the diaphragm is a significant component of the balanced armature driver that requires substantial selection effort, especially in the chemistry aspect.

This paper tackles how the current UV-cured adhesive connecting the drive rod to the diaphragm was carefully selected at Knowles Electronics Philippines after consideration of the general adhesive chemistry, curing mechanisms, material properties, product compatibility, manufacturability, and reliability.

The new adhesive used to attach the drive rod to the diaphragm enhanced the chemical resistance and overall reliability performance of the balanced armature driver. This enhancement was achieved without compromising the electroacoustic signature of the device and without affecting the assembly process or overall manufacturability.

1.0 INTRODUCTION

1.1 Background of the Study

Balanced armature[1] (BA) drivers are devices that convert electrical audio signals into mechanical wave energy, using the principle of electromagnetic induction.

A BA driver uses an electronic signal to cause a varying magnetic field in the coil to vibrate a tiny reed (armature) that is balanced between two magnets inside a tiny enclosure (thus the term balanced armature). The motion of the reed is transferred to a very stiff aluminum diaphragm through a drive rod which acts as a mechanical coupler. This diaphragm then produces the sound waves the user hears.

BA drivers are also referred to as BA receivers and are commonly used in hearing aids, in-ear monitors, and other compact audio devices. Figure 1 provides a cross-sectional view of a typical BA driver and how it is employed.

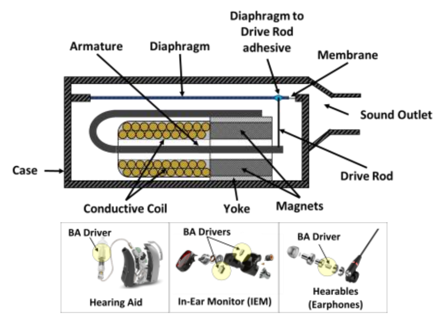


Fig. 1. Cross-section of a Balanced Armature Driver and Typical Application

All parts of a BA driver must be defect-free to function properly and according to its desired specifications.

One of the most important parts of a BA driver is the connection between the drive rod and the diaphragm. This is made with an adhesive and is crucial to withstand various factors such as environmental exposure, chemical exposure, abuse, and long-term usage. Therefore, it is vital to ensure that this connection is both reliable and durable, as it is expected to last the entire lifetime of the device.

1.2 Statement of the Problem

One customer of Knowles Electronics has reported a high failure rate in the field of certain batches of Model X BA drivers that they received which led to concerns about operational disruptions and product launch delays. It was crucial to address this issue promptly to minimize failures, ensure product reliability, and meet the customer's expectations. Failure analysis revealed that the failure mechanism is on the decoupling of the drive rod from the diaphragm due to weakness in drive rod adhesive bonding (see Figure 2).

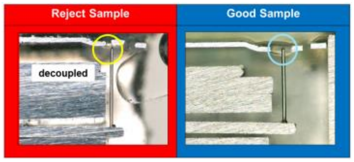


Fig. 2. Decoupled Drive Rod to Diaphragm Failure Mechanism

As shown in the Ishikawa Diagram in Figure 3, various factors were investigated that could have led to this failure mechanism of the detached drive rod to paddle.

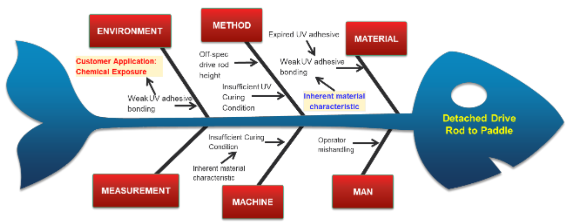


Fig. 3. Ishikawa Diagram for Detached Drive Rod to Paddle

The primary factor was identified to be the degradation of the drive rod adhesive due to chemical damage during customer field application. As a secondary factor, the existing UV-cured adhesive is not adequate to withstand chemical exposure due to its inherent material characteristics.

Process optimization efforts have previously been made but failures still manifested which prompted the team to check on the material characteristics of the existing UV adhesive being used in the drive rod to paddle attachment process.

1.3 Objective of the Study

This paper aims to address the detachment of the drive rod to the diaphragm through careful material selection of the UV-cured adhesive used in the bonding of the BA drivers.

1.4 Scope and Delimitations of the Study

This scope of the paper is on the material selection of UV adhesives used in the drive rod adhesive application process of BA drivers. The paper focuses on material as a factor and does not delve into the specifics of the other 4M factors (man, machine, method, milieu) which are covered with the full Six Sigma Black Belt project.

2.0 REVIEW OF RELATED WORK

Not applicable

3.0 METHODOLOGY

3.1 PDCA – Plan Phase

3.1.1 Review of Balanced Armature Driver Acoustic Requirements

In the design of most BA drivers, the motion of the reed must be directly translated to an equal motion of the diaphragm without any damping. To achieve this, the connection between the drive rod and the diaphragm should be as rigid as possible. To ensure rigid connection, the adhesive used to attach the drive rod to the diaphragm should have a Shore D hardness, specifically in the extra hard scale illustrated in the Shore Hardness Scale in Figure 4.

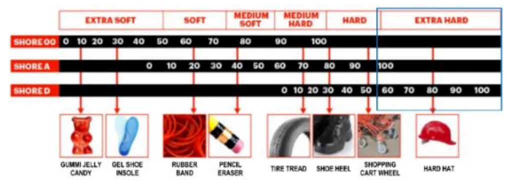


Fig. 4. Shore Hardness Scale

3.1.2 Review of Assembly Process Requirements

This particular model runs in a high volume and high turnaround time being processed in a fully automated production line (Figure 5). A fast-curing adhesive must be employed in the bonding of the drive rod to the diaphragm. This is essential to ensure that the drive rod to diaphragm adhesive application and curing process does not become the bottleneck in the overall production process. This can only be achieved if the adhesive's curing mechanism remains to be UV-cured.

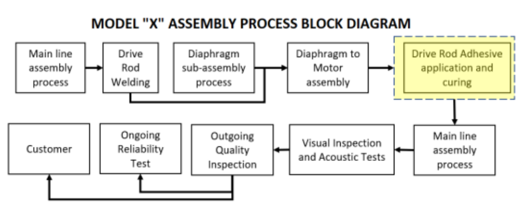


Fig. 5. Model "X" Assembly Process Block Diagram.

3.1.3 Review of Balanced Armature Driver Product Reliability Requirements

Knowles BA drivers should last the lifetime of the device it is being integrated into, withstanding normal use, wear and tear, mechanical and electrical stress, chemical exposure, environmental exposure, and even abuse by the user.

The drive rod to diaphragm connection mechanically coupled by the drive rod adhesive, should it fail after being compromised, will render the BA driver non-functional, and will no longer produce the desired sound output. Therefore, the drive rod adhesive must be at par with these rigorous requirements. The typical desired mechanical properties are adequate shear strength, high Young's modulus, low shrinkage rate, and low water absorption.

Figure 6 illustrates the mechanical forces the Drive Rod to Diaphragm connection experiences during operation.

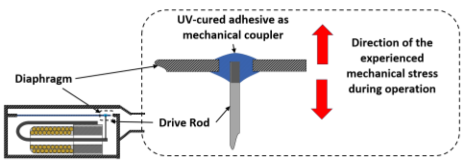


Fig. 6. Extreme close-up view of the Drive Rod to Diaphragm connection and the representation of the mechanical stress during operation.

3.1.4 General Adhesive Chemistry Review

3.1.4.1 Adhesive Material Comparison and Selection

Although the existing UV-cured adhesive being used in the attachment process of the drive rod to the diaphragm of the BA driver has previously passed qualification during the New Product Introduction (NPI) stage, subsequent failures were still encountered in the field. This indicates that the qualification was inadequate to capture the field failures and the UV-cured adhesive material was not robust enough to withstand the customer's application specifically when interacting with different chemicals (e.g. cleaning agents in hearing aids) used by the end user.

The existing UV-cured adhesive was then reviewed in terms of material characteristics. The review showed that the adhesive is an acrylate type of UV adhesive.

Based on the International Journal of Adhesion and Adhesives[2] (1991) and technical discussions with adhesive suppliers, epoxy-based UV-cured adhesives provide better chemical resistance and thermal stability compared to acrylate-based UV-cured adhesives. This makes epoxy-based UV-cured adhesives suitable for demanding applications where exposure to harsh environments or elevated temperatures is a concern which was primarily encountered in the customer field failures.

3.1.4.2 Polymerization Comparison: Epoxy vs Acrylate

Cationic polymerization[3], which is a characteristic of epoxy-based UV-cured adhesives, involves the formation of positively charged intermediates during the reaction process. These intermediates then initiate the polymerization of epoxide monomers, leading to the formation of crosslinked polymer networks.

Epoxy-based UV-cured adhesive polymerization:

$$Epoxy\ resin\ +\ Photoinitiator + UV\ light \rightarrow Polymer\ network$$

Acrylate-based UV-cured adhesive polymerization:

$$Acrylate\ monomers\ +\ Photoinitiator\ +\ UV\ light\ \rightarrow Polymerization$$

In epoxy-based UV-cured adhesive polymerization, the photoinitiator absorbs UV light, leading to the initiation of the polymerization process in the epoxy resin, resulting in the formation of a cross-linked polymer network. On the other hand, in acrylate-based UV-cured adhesive polymerization, the photoinitiator absorbs UV light, initiating the polymerization process in the acrylate monomers, leading to the formation of a polymer chain.

Overall, cationic polymerization in epoxy-based UV-cured adhesives offers advantages such as low shrinkage, excellent chemical resistance, and high-temperature stability. Moreover, epoxy-based UV-cured adhesive offers superior polymerization compared to acrylate-based UV-cured adhesive due to its higher cross-linking density and better adhesion properties.

3.1.4.3 Adhesive Parameters and Cured Properties

The team reviewed potential adhesive candidates from two manufacturers based on their parameters and cured properties. The replacement needs to have parameters such as viscosity, curing mechanism, irradiation time, and curing time similar to the current adhesive for manufacturability purposes and seamless transition. The cured properties of the replacement should be better or comparable, with a preference for higher hardness, tensile strength, and Young's Modulus, and minimized water absorption and shrinkage. The adhesive should also be compatible with the drive rod and diaphragm, which are made of stainless steel and aluminum respectively. Having no difference in cost was also desired. Additionally, the team also prioritized the advantages offered by an epoxy-based UV-cured adhesive, especially on its higher chemical resistance. Figure 7 shows the differences between these adhesives. Despite noting a potential manufacturability concern regarding the 24-hour full curing time of the epoxy-based adhesive, the team has ultimately decided to pursue the evaluation of adhesive (#3) from manufacturer B.

		A		B		
	Manufacturer	A		B		
	Adhesive	1	2	1	2	3
	Status	Current adhesive used	Potential candidates for evaluation			
	Chemical base	Acrylate	Acrylate	Acrylate	Acrylate	**Epoxy**
Parameters	Curing mechanism	Dual UV Light/ Heat curing	**Dual** **UV Light/humidity-curing**	Single UV Light-curing	Single UV Light-curing	Single UV Light-curing
	Irradiation time (365nm)	10s (UV)	**2s**	3s	5s	10s
	Curing time	10s (UV)/ 60min (Heat)	**2s**	3s	5s	24hrs
	Viscosity (mPas)	27000 (Brookfield)	**20,000** **(rheometer, 2 1/s)**	5500	90,000 (Brookfield)	8,400 (rheometer, 10 1/s)
Cured Properties	Compatability with Drive Rod and Diaphragm material (SS, Alu)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
	Typical area of use (Temp range)	NA	NA	-40~120°C	-40~120°C	**-40~180°C**
	Hardness (Shore)	D80	D40	D70	D60	**D85**
	Tensile Strength (MPa)	25.7	14	13.8	22	**50**
	YM (MPa)	611	150	444.8	900	**3400**
	Water Absorption (%)	1.4	3	**0.1**	1.2	0.3
	Shrinkage, (vol %)	0.2	7	**0.7**	7.5	3.9

Fig. 7. Adhesive Parameters and Cured Properties Comparison

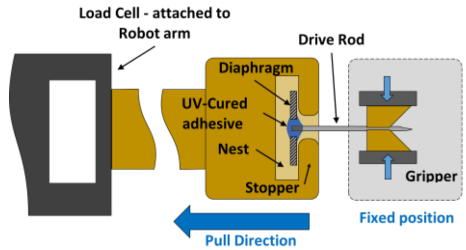


Fig. 8. Close-up view of the illustration of the Drive Rod to Diaphragm Pull-Out test mechanism.

3.2 PDCA – Do Phase

3.2.1 Material-Level Qualification

Before the UV-cured adhesives were assembled into the BA drivers, they were exposed to certain material-level tests such as the Cataplasma Test, Direct Chemical Exposure Tests, and the Drive Rod to Diaphragm Pull-Out Test.

3.2.1.1 Cataplasma Tests

During the Cataplasma Test, the adhesives were applied to the drive rod and diaphragm, without completely assembling the BA driver. The samples were then submerged in water at a temperature of 70ºC for 4 and 8 hours respectively. Following the exposure, the adhesives were visually examined for any defects or changes in their appearance.

3.2.1.2 Direct Contact Chemical Exposure Tests

In the Direct Contact Chemical Exposure Test, chemicals were directly applied to the adhesives, without completely assembling the BA driver. The samples were then stored at room temperature for 24 hours. Following the exposure, the adhesives were visually examined for any defects or changes in their appearance. The chemicals (e.g. sunscreen, perfume, alcohol, sweat solution) chosen for the study are the typical chemicals the BA drivers are exposed to in the field.

3.2.1.3 Mechanical Test (Drive Rod to Diaphragm Pull-out Test)

The drive rod to the diaphragm pull-out test was developed at Knowles to check for the shear strength of the bond of the drive rod to the adhesive connecting it to the diaphragm. It is highly useful in the characterization and comparison of both acrylate-based and epoxy-based UV-cured adhesives. In this test, the Force to break the drive rod (F) from the adhesive was measured through the pulling mechanism. This is illustrated in Figure 8.

3.2.2 Balanced Armature Driver-Level Qualification

Fully assembled BA drivers incorporating the acrylate-based UV-cured adhesive (control group) and epoxy-based UV-cured adhesive (trial group) were then subjected to Finished Goods (FG-level) Qualification. Both the control group and trial group were assembled in the same line, using the same material lots and equipment, minimizing the variabilities to only the types of adhesives used in the drive rod to diaphragm connection.

3.2.2.1 Acoustic Evaluation

Before making any design or material changes to the BA driver, it is crucial to conduct an electroacoustic evaluation. It is also essential to maintain a consistent acoustic signature; any variation will affect the overall performance and consequently impact the module level at the customer assembly.

3.2.2.2 Process Qualification

A full-factorial Design of Experiment (DOE) was to be conducted to optimize the Drive Rod Adhesive Application & Curing Station. As outlined in Figure 9, the input variables considered in the DOE plan are: dispense pressure, dispense time, and needle diameter while the output responses are the Pull-Out Force and adhesive dispense coverage.

Input Variables	Levels	Output Variables	Levels	Target
Dispense Pressure (MPa)	constant (0.2MPa)	Pull-out Force (N)	numeric	maximize
Dispense Time (s)	4 levels (0.05s, 0.1s, 0.2s, 0.3s)	Coverage	3 levels (-1 insufficient, 0 sufficient, 1 excessive)	0 (sufficient coverage)
Needle Diameter (gauge)	2 levels (32 gauge, 34 gauge)			

Fig. 9. Key Process Input and Output Variables

The impact on the manufacturability in terms of parameters set-up, Overall Equipment Effectiveness (OEE), and overall assembly yield was assessed. Small-scale and large-scale trial runs were performed to validate the performance.

3.2.2.3 Product Reliability Testing

Comprehensive FG-level reliability testing was performed to assess and simulate the performance of the BA drivers under accelerated and extreme conditions. Ten various tests were performed which were either environmental or mechanical.

Reliability tests 1b and 3b (extended iterations of HALT and E3) and Reliability tests 7 to 10 involving chemical exposure and extreme temperature conditions were specifically introduced in the FG-level testing. These are not the typical tests that Knowles performs during product qualification. However, since the current UV-cured adhesive passed qualification, it was prudent that new reliability tests be introduced to replicate the failures found by the customer in the field (see Figure 10). As for the chemicals used in the Vaporized Chemical Tests, these are the same chemicals used in the Direct Contact Chemical Exposure Tests.

#	Test	Condition	Criteria (Must Pass)
1a	HALT (Highly Accelerated Life Test)	Exposed at high temp and humidity at increased voltage drive level, 6 weeks	BA Acoustic Performance
1b	Extended HALT (Highly Accelerated Life Test)	Exposed at high temp and humidity at increased voltage drive level, 12 weeks	
2	High Drive Stress Test	Continuous drive at elevated voltages, 1 hour	
3a	Environment 3	Exposed to high temp and humidity, no drive, 6 weeks	
3b	Extended Environment 3	Exposed to high temp and humidity, no drive, 12 weeks	
4	Temperature Humidity Cyclic Test	Cyclic low and high temp exposure, 10 cycles	
5	Low-Temperature Storage	Negative temperature exposure, 72 hours	
6	Mechanical Shock	Dropped at progressive heights until failure	
7	Vaporized Chemical Exposure Test	Exposed to 8 different types of chemicals, 24 hours	BA Acoustic Performance + Adhesive Visual condition
8	Vaporized Chemical Exposure + High Drive Stress Test	Combination of Chemical Exposure Test (24, 48, 72 hrs) and High Drive Stress Test (3 hrs)	
9	Low Temperature Storage + High Drive Stress Test	Combination of Low Temp Storage (72, 96, 120, 144 hrs) and High Drive Stress Test (3 hrs)	
10	Vaporized Chemical Exposure Test + Low-Temperature Storage Test	Combination of Chemical Exposure (24, 48, 72 hrs) and Low Temp Storage Test (48 hrs)	

Fig. 10. Product Reliability Test Conditions

4.0 RESULTS AND DISCUSSION

4.1 PDCA – Check Phase

4.1.1 Material-Level Qualification Results

4.1.1.1 Cataplasma Test Results

Figure 11 shows the comparison of the drive rod to diaphragm adhesive visual condition after the Cataplasma testing. The Trial Group, which uses the epoxy-based UV-cured adhesive performed better in terms of the surface deterioration of the adhesive compared to the Control Group (using the Acrylate-based).

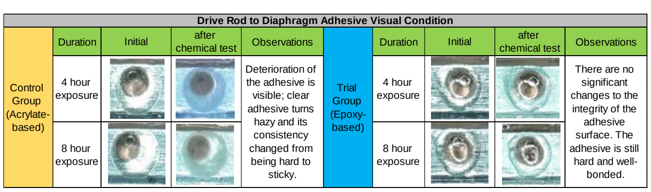


Fig. 11. Drive Rod to Diaphragm Adhesive Visual Condition Comparison after the Cataplasma Test

4.1.1.2 Direct Contact Chemical Exposure Test Results

The comparison results of the visual condition of the drive rod to diaphragm adhesive after the Direct Contact Chemical Exposure Test are presented in Figure 12. The Control Group, which used the acrylate-based adhesive, showed minimal surface deterioration in five out of the eight chemicals. The Trial Group, which used the epoxy-based adhesive did not show these similar signs of surface deterioration. Please see Appendix A for the before and after images of the adhesives exposed to all chemicals.

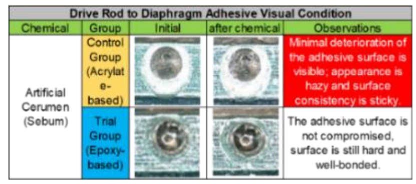


Fig. 12. Drive Rod to Diaphragm Adhesive Visual Condition Comparison after the Direct Contact Chemical Exposure Test

4.1.1.3 Mechanical Test (Drive Rod to Diaphragm Pull-out Test) Results

In Figure 13, the comparison of the Drive Rod to Diaphragm Pull-Out Test Data can be seen after complete curing. The data indicates that the Force to Break for the Trial Group (epoxy-based) is significantly better than that of the Control Group (acrylate-based). However, the data was collected in different time intervals for the two groups. The Control Group data was taken @ t=0 since acrylate-based UV-cured adhesives immediately attain full cure characteristics, while the Trial Group data was taken after 24 hours, which is the time required for the epoxy-based UV-cured adhesive to achieve its full cure condition. For the comprehensive statistical analysis, please refer to Appendices B to G.

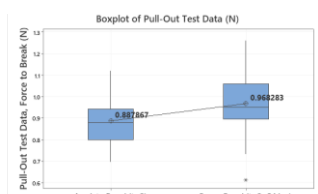


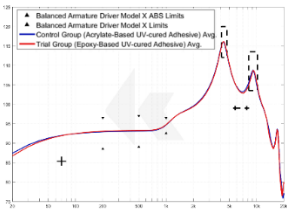
Fig. 13. Drive Rod to Diaphragm Pull-Out Test Data (Force to Break in N)

4.1.2 Balanced Armature Driver-Level (FG-Level) Qualification Results

4.1.2.1 Acoustic Evaluation Results

Figure 14 shows the comparison of acoustic signatures between groups that used different drive rod to diaphragm adhesives: Acrylate-based UV-cured Adhesives vs Epoxy-based UV-cured Adhesives. A comparison was done on the sensitivity (Y-axis) of the Balanced Armature Drivers at certain Frequencies (X-axis) as well as the Process Capability of key parameters.

The results indicate that there are no significant changes to the acoustic response of the BA driver. The detailed Process Capability analysis can be seen on Appendices H to U.



Acoustic Parameter	Process Capability (PpK)		Remarks
	Control	Trial	
SENSITIVITY A	1.96	1.85	pass
SENSITIVITY B	2.34	2.49	pass
SENSITIVITY C	1.70	1.98	pass
THD-1	1.71	2.00	pass
THD-2	1.33	1.35	pass
IMPEDANCE-1	1.64	2.14	pass
IMPEDANCE-2	1.86	2.17	pass

Fig. 14. Acoustic Response and Acoustic Parameters Cpk Comparison

4.1.2.2 Process Qualification Results

The optimized process parameters based on the DOE are shown in Figure 15. The relevant statistical analyses (regression, residual and main effects plots, response prediction) as to how these parameters were derived can be seen in Appendices V to Z. Cpk analysis on the resulting adhesive amount (in mg) is provided in Appendix AA.

Parameters	Existing Set-up	New Set-up	Set-up change
Dispense Pressure (Mpa)	0.2MPa	0.2MPa	None (same settings)
Dispense Time (s)	0.3s	0.1s	Reduced (due to lower viscosity of the Epoxy-based adhesive)
Needle Diameter (gauge)	#32 gauge	#34 gauge	Changed to thinner diameter (due to lower viscosity of the Epoxy-based adhesive)
Irradiation Time (s)	18s	18s	None (same settings to minimize changes to the line) 365nm flood type,@ min 1.67W/cm² and max 4.17W/cm²)
Adhesive Amount (mg)	0.4~0.8mg	0.3~0.5mg	Optimized amount based on new Dispense time and Needle diameter

Fig. 15. Optimized DR Adhesive Application & Curing Station Process Parameters

Small-scale and large-scale runs resulted in a stable overall yield and station OEE of above 95%. There were notable setup and equipment downtime occurrences with the transition to the epoxy-based UV-cured adhesive.

In summary, results were deemed to be favorable for the Trial Group using the epoxy-based UV-cured adhesive.

4.1.2.3 Product Reliability Testing Results

The results of FG-level reliability testing are shown in Figure 16. The Control group, which utilized the acrylate-based UV-cured adhesive, failed to meet the newly introduced reliability testing conditions and the extended iteration of HALT. The qualitative evaluation of the Drive Rod visual conditions and the Pull-Out Test Data after the Vaporized Chemical Testing revealed unfavorable results. The Force to Break on the Control group in comparison to the Trial group is observed to be lower. On the samples exposed to perfume, the Control Group was unable to be tested due to extreme degradation of the acrylate-based adhesive. Quantitative comparison however is available on samples exposed to the household cleaner. Please see Appendix BB for the representative images and Appendices CC to FF on the Pull-out Test data.

#	Test	Group	Results			
			BA Acoustic Performance	Adhesive Visual condition	Pull-Out Test	Overall Judgement
1a	HALT (Highly Accelerated Life Test)	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
1b	Extended HALT (Highly Accelerated Life Test)	Control (Acyrylate-based)	FAIL			FAIL
		Trial (Epoxy-based)	PASS			PASS
2	High Drive Stress Test	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
3a	Environment 3	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
3b	Extended Environment 3	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
4	Temperature Humidity Cyclic Test	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
5	Low-Temperature Storage	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
6	Mechanical Shock	Control (Acyrylate-based)	PASS			PASS
		Trial (Epoxy-based)	PASS			PASS
7	Vaporized Chemical Exposure Test	Control (Acyrylate-based)	PASS	FAIL	Lower Force to Break (N)	FAIL
		Trial (Epoxy-based)	PASS	PASS	Higher Force to Break (N)	PASS
8	Vaporized Chemical Exposure + High Drive Stress Test	Control (Acyrylate-based)	PASS	FAIL		FAIL
		Trial (Epoxy-based)	PASS	PASS		PASS
9	Low Temperature Storage + High Drive Stress Test	Control (Acyrylate-based)	PASS	FAIL		FAIL
		Trial (Epoxy-based)	PASS	PASS		PASS
10	Vaporized Chemical Exposure Test + Low-Temperature Storage Test	Control (Acyrylate-based)	PASS	FAIL		FAIL
		Trial (Epoxy-based)	PASS	PASS		PASS

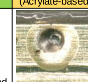
Drive Rod to Diaphragm Adhesive Visual Condition			
Test		Control Group (Acrylate-based)	Observations
7	Vaporized Chemical Exposure Test		Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)	Observations
			The adhesive surface is not compromised, surface is still hard and well-bonded.

Fig. 16. Product Reliability Testing Results and Sample Images of the Drive Rod to Diaphragm Adhesive Visual Condition Comparison after the Vaporized Chemical Exposure Tests

4.1.3 Implementation

The team was positioned to implement the epoxy-based UV-cured adhesive, replacing the acrylate-based UV-cured adhesive in bonding the drive rod to the diaphragm of Knowles Model X BA drivers with the favorable manufacturability and reliability performance without significant impact to material and operational cost.

4.1.4 Effectiveness Monitoring

4.1.4.1 Process Control Performance

Monitoring of the performance of the Drive Rod to Diaphragm Pull-out testing through Statistical Process Control is necessary to check for excursions through an X-bar and S chart (see Figure 17). The sample size and frequency of testing were set at 10 units per shift. Results indicate that the mean of the Force to Break (N) increased since the implementation of the epoxy-based UV-cured adhesive.

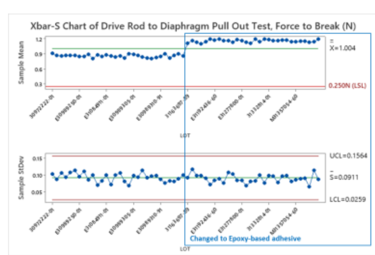


Fig. 17. Xbar-S Chart of the Diaphragm to Drive Rod Pull-Out Test Data

4.1.4.2 Ongoing Reliability Test (ORT)

The reliability performance of the BA drivers using the newly introduced epoxy-based UV-cured drive rod to diaphragm adhesive was monitored and tested in the reliability tests as shown in Figure 18. There were no reliability failures encountered since the implementation of the epoxy-based UV-cured adhesive.

#	Test	Condition	Criteria (Must Pass)
1	HALT (Highly Accelerated Life Test)	Exposed at high temp and humidity at increased voltage drive level, 6 weeks	BA Acoustic Performance
2	High Drive Stress Test	Continuous drive at elevated voltages, 1 hour	
3	Environment 3	Exposed to high temp and humidity, no drive, 6 weeks	
4	Temperature Humidity Cyclic Test	Cyclic low and high temp exposure, 10 cycles	
5	Low-Temperature Storage	Negative temperature exposure, 72 hours	
6	Mechanical Shock	Dropped at progressive heights until failure	
7	Vaporized Chemical Exposure Test	Exposed to 8 different types of chemicals, 24 hours	BA Acoustic Performance + Adhesive Visual condition
8	Vaporized Chemical Exposure + High Drive Stress Test	Combination of Chemical Exposure Test (24, 48, 72 hrs) and High Drive Stress Test (3 hrs)	
9	Low Temperature Storage + High Drive Stress Test	Combination of Low Temp Storage (72, 96, 120, 144 hrs) and High Drive Stress Test (3 hrs)	
10	Vaporized Chemical Exposure Test + Low-Temperature Storage Test	Combination of Chemical Exposure (24, 48, 72 hrs) and Low Temp Storage Test (48 hrs)	

Fig. 18. Ongoing Reliability (ORT) Test Conditions

4.2 PDCA – Act Phase

4.2.1 Documentation and Change Management Review of applicability to other part numbers

Documents affected by the change such as the Bill of Materials (BOM), PFMEA, Control Plan, Work Instructions, and Process Specifications were revised. Respective PCNs were also sent to key customers for approval before implementation.

5.0 CONCLUSION

It is concluded that careful material selection is vital for the type of UV-cured adhesive being used in balanced armature drivers. The conclusion is being made based on the results of the study which showed that epoxy-based UV-cured adhesives demonstrated superior bonding of the drive rod to the diaphragm and were able to withstand the harsh chemical exposure that the balanced armature drivers may be exposed to during customer application.

6.0 RECOMMENDATIONS

The proponents of the study recommend performing similar studies on other UV-cured adhesives being used in other manufacturing processes of Knowles Electronics.

It is also recommended to include Chemical Exposure Testing during the product qualification process of balanced armatures. This would ensure that vulnerabilities to chemical damage are exposed early on.

In addition, the review of the chemistry of the adhesive needs to be incorporated in the Design for Quality (DfQ) as part of the design review during the NPI stage.

7.0 ACKNOWLEDGMENT

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

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. The Chemistry and Applications of UV-cured Adhesives in International Journal of Adhesion and Adhesives, 1992, pp 183-186.

3. Review on UV-Induced Cationic Frontal Polymerization of Epoxy Monomers. (2020). https://www.researchgate.net/publication/344321190_Review_on_UV-Induced_Cationic_Frontal_Polymerization_of_Epoxy_Monomers

9.0 ABOUT THE AUTHORS

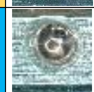
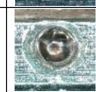
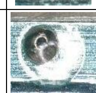
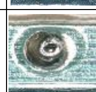
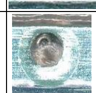
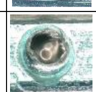
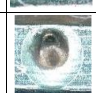
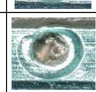
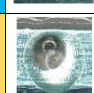
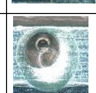
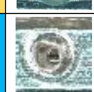
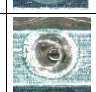
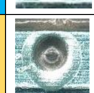
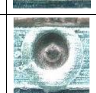
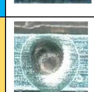
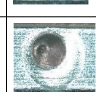
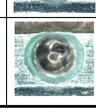
Dominic John P. Patarata is a graduate of the University of St. La Salle–Bacolod, a licensed Electronics Engineer, and a certified Six Sigma Green Belt practitioner. He is already Six Sigma Black Belt trained and pursuing his certification. He has been a Quality Engineer at the Camera Division of Cebu Mitsumi Inc. for 4 years and is currently a Sr. Quality Engineer at Knowles Electronics (Philippines) Corporation for 9 years. He also participated in the 2023 ASEMEP National Technical Symposium and won 1st Runner-up for the Best Paper and the Best Presenter (Day 2) for the FA/Reliability Track for his paper entitled "*Outright Detection Of Drive Rod To Diaphragm Assembly-Level Reliability Failures*".

Butch Angelo A. Aglibot is a graduate of the Cebu Institute of Technology University, a licensed Electronics Engineer, and a certified Six Sigma Green Belt practitioner. He has been a Quality Engineer at the Surface Mount Device (SMD) Inductor Division of Taiyo Yuden Phils. Inc – Cebu for 12 years and is currently a Quality Engineer at Knowles Electronics (Philippines) Corporation for 2 years.

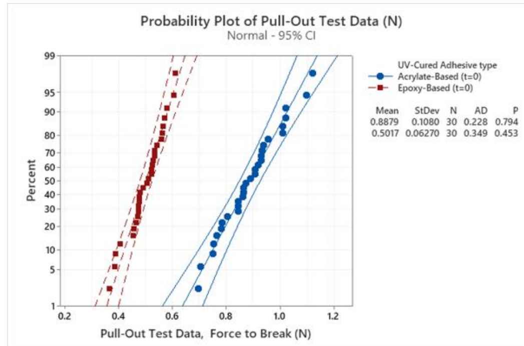
10.0 APPENDICES

Appendix A – Images of the Drive Rod to Diaphragm Adhesive Visual Condition Comparison after the Direct Contact Chemical Exposure Test

Drive Rod to Diaphragm Adhesive Visual Condition

Chemical		Group	Initial	after chemical	Observations
1	Artificial Cerumen (Sebum)	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
2	Sunscreen (Ladival)	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
3	Machine Oil	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
4	Perfume	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
5	70% Alcohol	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
6	Cleaning Spray (Connex)	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
7	pH 1.8 Sweat Solution	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.
8	Household Cleaner (Ajax)	Control Group (Acrylate-based)			Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.
		Trial Group (Epoxy-based)			The adhesive surface is not compromised, surface is still hard and well-bonded.

Appendix B - Normality Test of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0)



Appendix C - Test for Equal Variances of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0)

Method

σ_1: standard deviation of Pull-Out Test Data (N) when UV-Cured Adhesive type = Acrylate-Based (t=0)
σ_2: standard deviation of Pull-Out Test Data (N) when UV-Cured Adhesive type = Epoxy-Based (t=0)
Ratio: σ_1/σ_2
The Bonett and Levene's methods are valid for any continuous distribution.

Descriptive Statistics

UV-Cured Adhesive type	N	StDev	Variance	95% CI for σ
Acrylate-Based (t=0)	30	0.108	0.012	(0.087, 0.144)
Epoxy-Based (t=0)	30	0.063	0.004	(0.050, 0.084)

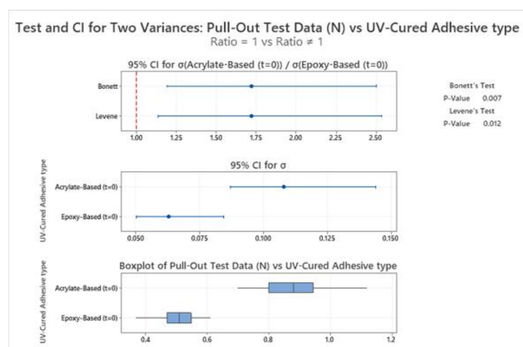
Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using Bonett	95% CI for Ratio using Levene
1.72178	(1.195, 2.503)	(1.138, 2.535)

Test

Null hypothesis $H_0: \sigma_1 / \sigma_2 = 1$
Alternative hypothesis $H_1: \sigma_1 / \sigma_2 \neq 1$
Significance level $\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
Bonett	7.37	1		0.007
Levene	6.66	1	58	0.012



Appendix D - Test for Equal Means of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0)

Method

μ_1: population mean of Pull-Out Test Data (N) when UV-Cured Adhesive type = Acrylate-Based (t=0)
μ_2: population mean of Pull-Out Test Data (N) when UV-Cured Adhesive type = Epoxy-Based (t=0)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Pull-Out Test Data (N)

UV-Cured Adhesive type	N	Mean	StDev	SE Mean
Acrylate-Based (t=0)	30	0.888	0.108	0.020
Epoxy-Based (t=0)	30	0.5017	0.0627	0.011

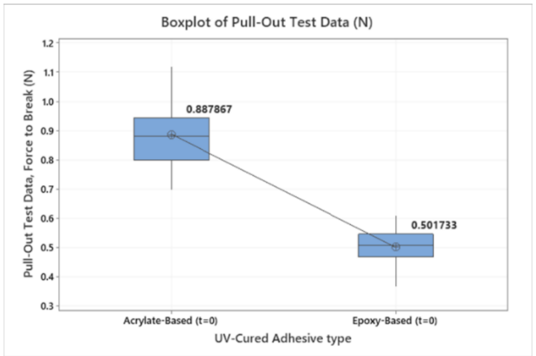
Estimation for Difference

Difference	95% CI for Difference
0.3861	(0.3403, 0.4320)

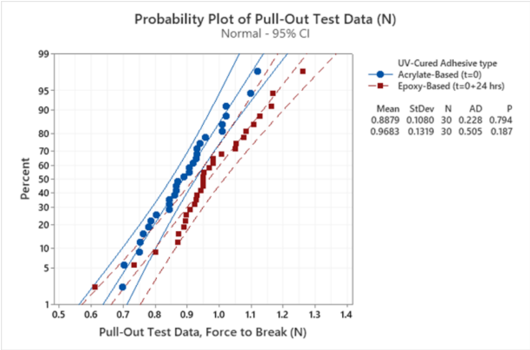
Test

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

T-Value	DF	P-Value
16.94	46	0.000



Appendix E - Normality Test of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0 +24 hrs.)



Appendix F - Test for Equal Variances of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0+24 hrs.)

Method

σ_1: standard deviation of Pull-Out Test Data (N) when UV-Cured Adhesive type = Acrylate-Based (t=0)
σ_2: standard deviation of Pull-Out Test Data (N) when UV-Cured Adhesive type = Epoxy-Based (t=0+24 hrs)
Ratio: σ_1/σ_2
The Bonett and Levene's methods are valid for any continuous distribution.

Descriptive Statistics

UV-Cured Adhesive type	N	StDev	Variance	95% CI for σ
Acrylate-Based (t=0)	30	0.108	0.012	(0.087, 0.144)
Epoxy-Based (t=0+24 hrs)	30	0.132	0.017	(0.098, 0.190)

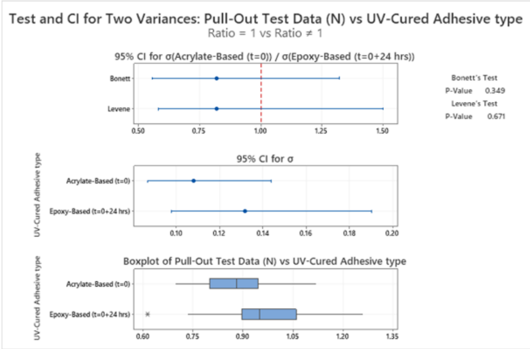
Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using Bonett	95% CI for Ratio using Levene
0.818543	(0.555, 1.321)	(0.580, 1.503)

Test

Null hypothesis $H_0: \sigma_1 / \sigma_2 = 1$
Alternative hypothesis $H_1: \sigma_1 / \sigma_2 \neq 1$
Significance level $\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
Bonett	0.88	1		0.349
Levene	0.18	1	58	0.671



Appendix G - Test for Equal Means of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive (t=0) vs Epoxy-Based UV-cured adhesive (t=0+24 hrs.)

Method

μ_1: population mean of Pull-Out Test Data (N) when UV-Cured Adhesive type = Acrylate-Based (t=0)
μ_2: population mean of Pull-Out Test Data (N) when UV-Cured Adhesive type = Epoxy-Based (t=0+24 hrs)
Difference: $\mu_1 - \mu_2$

Equal variances are assumed for this analysis.

Descriptive Statistics: Pull-Out Test Data (N)

UV-Cured Adhesive type	N	Mean	StDev	SE Mean
Acrylate-Based (t=0)	30	0.888	0.108	0.020
Epoxy-Based (t=0+24 hrs)	30	0.968	0.132	0.024

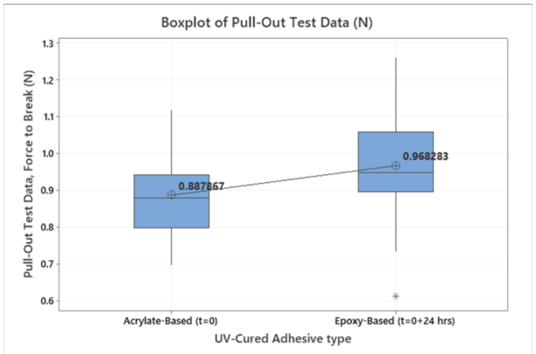
Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
-0.0804	0.1205	(-0.1427, -0.0181)

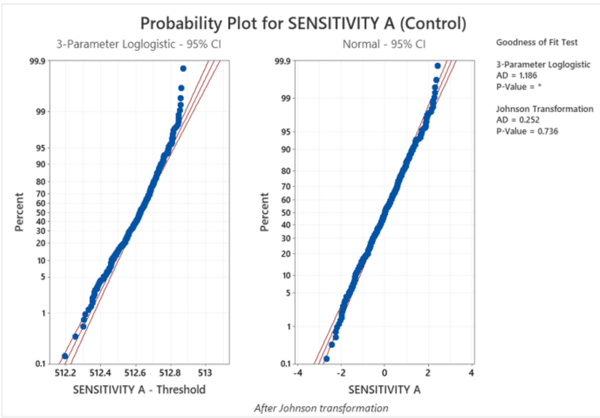
Test

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

T-Value	DF	P-Value
-2.58	58	0.012

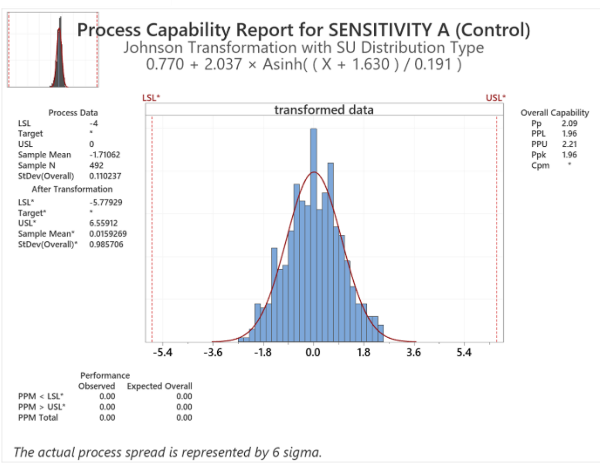


Appendix H– Process Capability Analysis of SENSITIVITY A (Control; Acrylate-Based UV Adhesive) Parameter

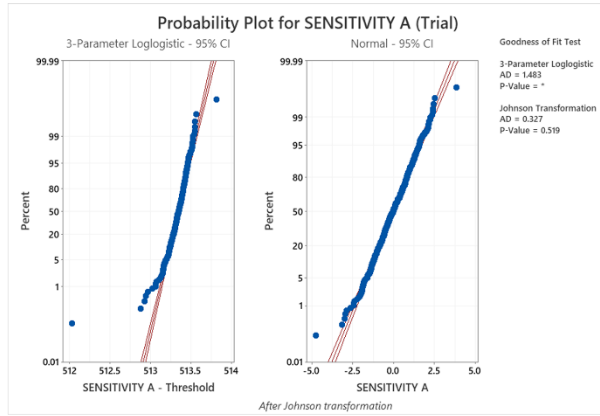


Goodness of Fit Test

Distribution	AD	P
Normal	1.914	<0.005
3-Parameter Lognormal	1.913	*
2-Parameter Exponential	123.676	<0.010
3-Parameter Weibull	0.573	0.084
Smallest Extreme Value	2.467	<0.010
Largest Extreme Value	14.654	<0.010
3-Parameter Gamma	3.069	*
Logistic	1.183	<0.005
3-Parameter Loglogistic	1.186	*
Johnson Transformation	0.252	0.736

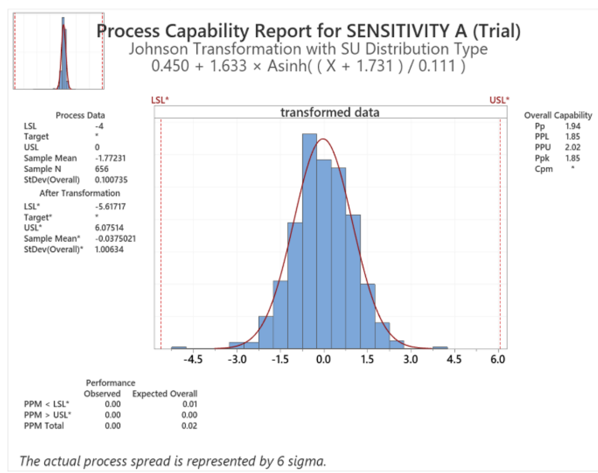


Appendix I– Process Capability Analysis of SENSITIVITY A (Trial; Epoxy-Based UV Adhesive) Parameter

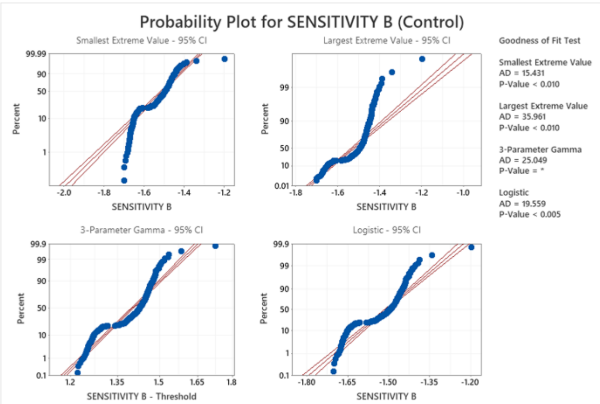


Goodness of Fit Test

Distribution	AD	P
Normal	12.930	<0.005
3-Parameter Lognormal	12.898	*
2-Parameter Exponential	264.041	<0.010
3-Parameter Weibull	16.869	<0.005
Smallest Extreme Value	23.689	<0.010
Largest Extreme Value	124.622	<0.010
3-Parameter Gamma	18.465	*
Logistic	1.481	<0.005
3-Parameter Loglogistic	1.483	*
Johnson Transformation	0.327	0.519

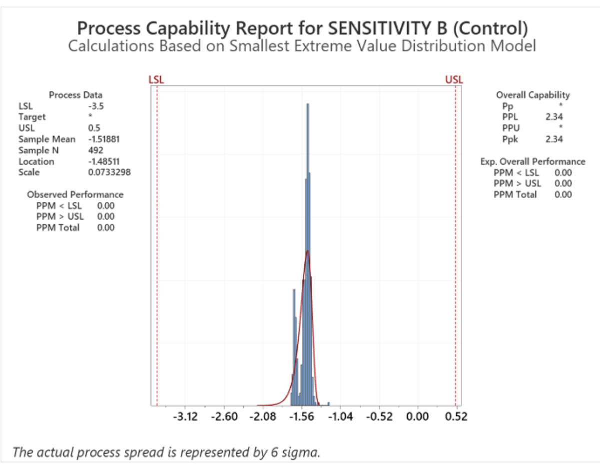


Appendix J– Process Capability Analysis of SENSITIVITY B (Control; Acrylate-Based UV Adhesive) Parameter

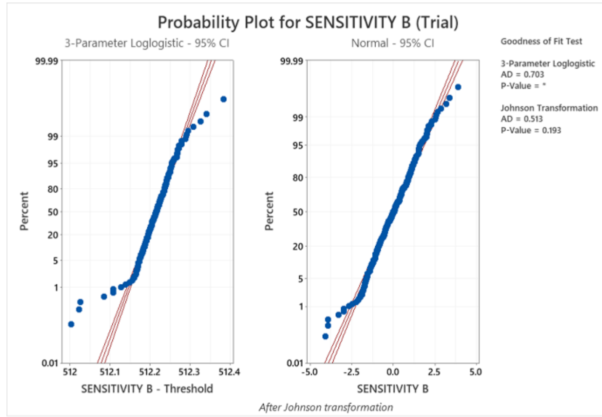


Goodness of Fit Test

Distribution	AD	P
Normal	23.420	<0.005
3-Parameter Lognormal	23.454	*
2-Parameter Exponential	81.857	<0.010
3-Parameter Weibull	16.300	<0.005
Smallest Extreme Value	15.431	<0.010
Largest Extreme Value	35.961	<0.010
3-Parameter Gamma	25.049	*
Logistic	19.559	<0.005
3-Parameter Loglogistic	19.564	*

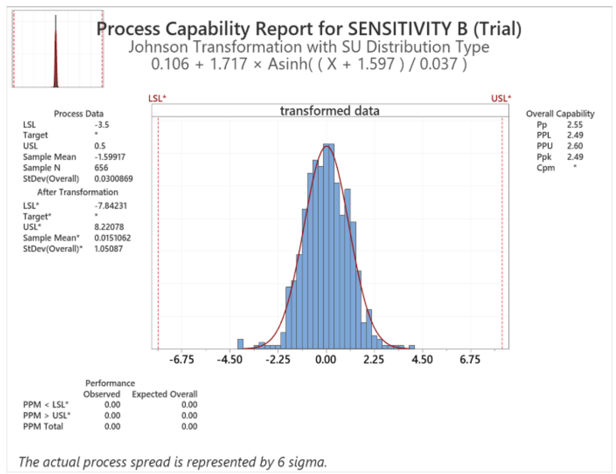


Appendix K– Process Capability Analysis of SENSITIVITY B (Trial; Epoxy-Based UV Adhesive) Parameter

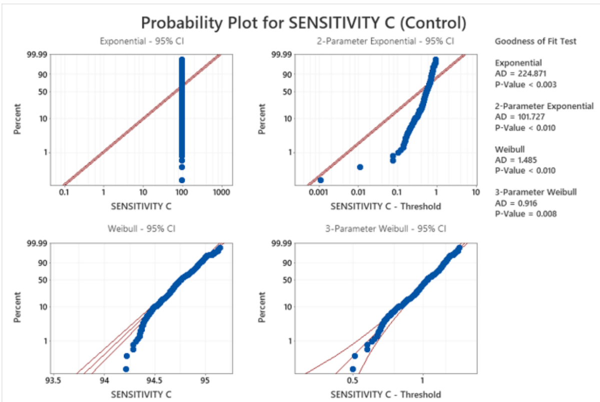


Goodness of Fit Test

Distribution	AD	P
Normal	7.675	<0.005
3-Parameter Lognormal	7.628	*
2-Parameter Exponential	230.858	<0.010
3-Parameter Weibull	20.085	<0.005
Smallest Extreme Value	37.265	<0.010
Largest Extreme Value	67.574	<0.010
3-Parameter Gamma	9.755	*
Logistic	0.708	0.039
3-Parameter Loglogistic	0.703	*
Johnson Transformation	0.513	0.193

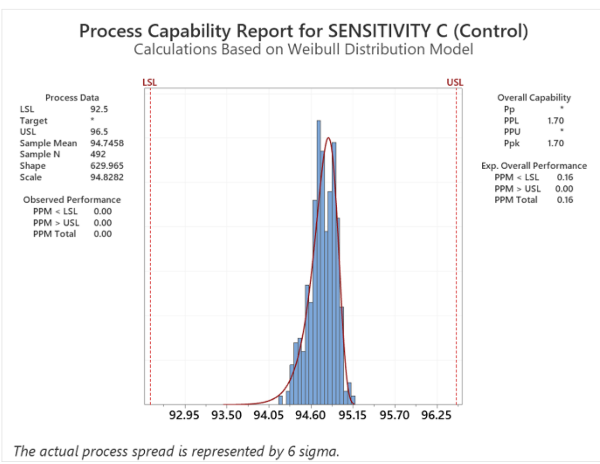


Appendix L– Process Capability Analysis of SENSITIVITY C (Control; Acrylate-Based UV Adhesive) Parameter

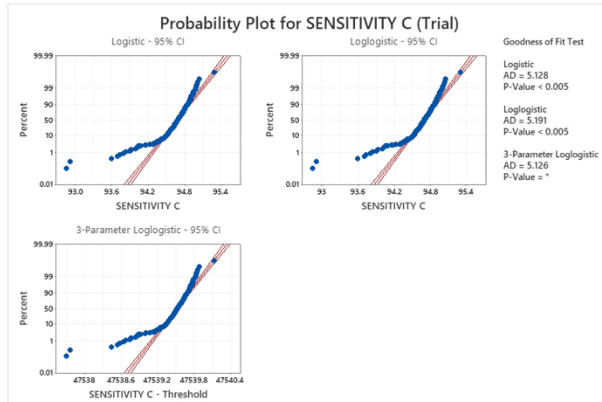


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	2.674	<0.005	
Box-Cox Transformation	2.551	<0.005	
Lognormal	2.705	<0.005	
3-Parameter Lognormal	2.679	*	0.523
Exponential	224.871	<0.003	
2-Parameter Exponential	101.727	<0.010	0.000
Weibull	1.485	<0.010	
3-Parameter Weibull	0.916	0.008	0.000
Smallest Extreme Value	1.503	<0.010	
Largest Extreme Value	12.967	<0.010	
Gamma	2.700	<0.005	
3-Parameter Gamma	3.599	*	1.000
Logistic	2.450	<0.005	
Loglogistic	2.466	<0.005	
3-Parameter Loglogistic	2.450	*	0.610

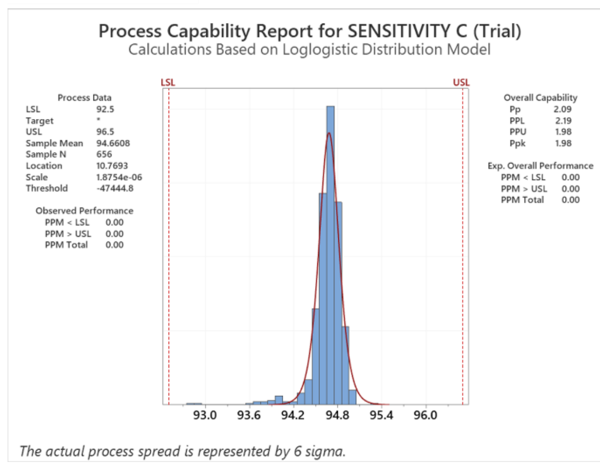


Appendix M– Process Capability Analysis of SENSITIVITY C (Trial; Epoxy-Based UV Adhesive) Parameter

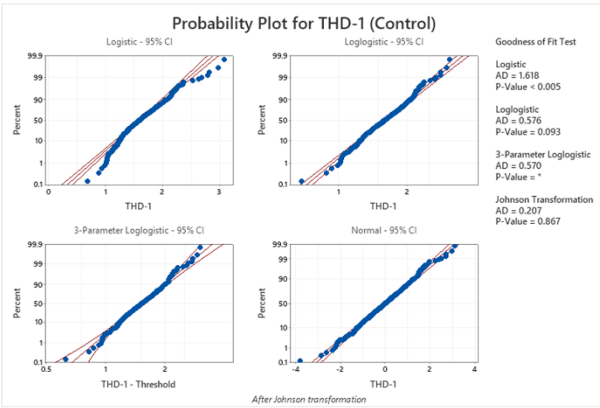


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	27.126	<0.005	
Box-Cox Transformation	25.739	<0.005	
Lognormal	27.484	<0.005	
3-Parameter Lognormal	27.071	*	0.030
Exponential	299.874	<0.003	
2-Parameter Exponential	249.644	<0.010	0.000
Weibull	10.936	<0.010	
3-Parameter Weibull	10.235	<0.005	0.122
Smallest Extreme Value	10.955	<0.010	
Largest Extreme Value	108.438	<0.010	
Gamma	27.309	<0.005	
3-Parameter Gamma	32.759	*	1.000
Logistic	5.128	<0.005	
Loglogistic	5.191	<0.005	
3-Parameter Loglogistic	5.126	*	0.195

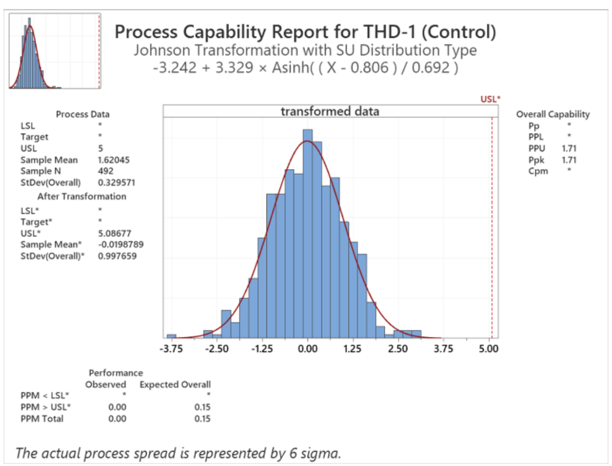


Appendix N– Process Capability Analysis of THD-1 (Control; Acrylate-Based UV Adhesive) Parameter

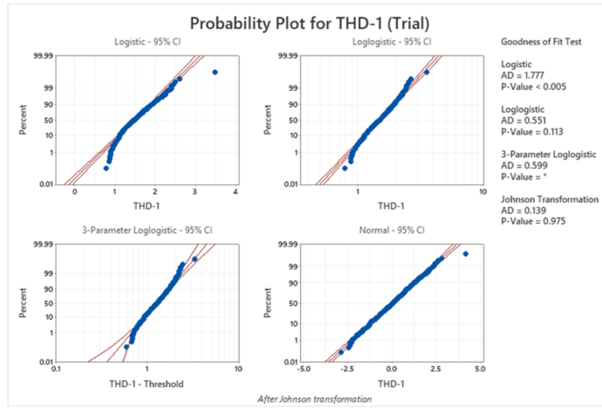


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	2.144	<0.005	
Box-Cox Transformation	0.209	0.864	
Lognormal	0.209	0.864	
3-Parameter Lognormal	0.221	*	0.543
Exponential	147.122	<0.003	
2-Parameter Exponential	98.074	<0.010	0.000
Weibull	6.609	<0.010	
3-Parameter Weibull	2.505	<0.005	0.000
Smallest Extreme Value	18.647	<0.010	
Largest Extreme Value	1.262	<0.010	
Gamma	0.425	>0.250	
3-Parameter Gamma	0.284	*	0.265
Logistic	1.618	<0.005	
Loglogistic	0.576	0.093	
3-Parameter Loglogistic	0.570	*	0.859
Johnson Transformation	0.207	0.867	

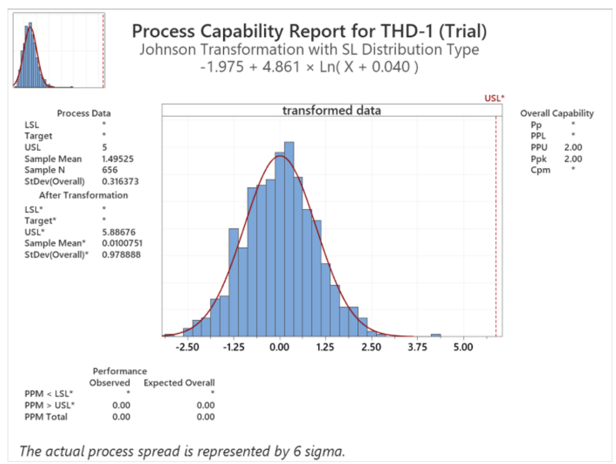


Appendix O– Process Capability Analysis of THD-1 (Trial; Epoxy-Based UV Adhesive) Parameter

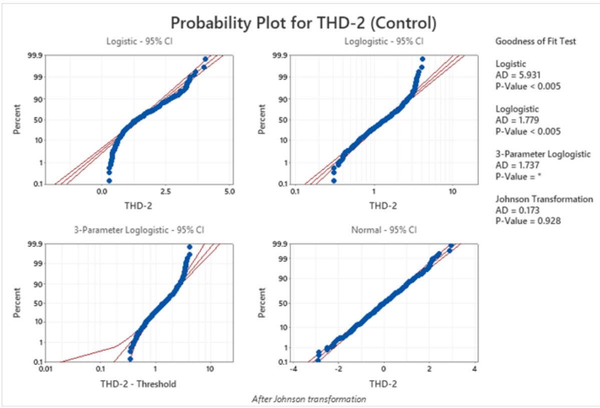


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	2.934	<0.005	
Box-Cox Transformation	0.141	0.973	
Lognormal	0.141	0.973	
3-Parameter Lognormal	0.186	*	0.496
Exponential	192.858	<0.003	
2-Parameter Exponential	94.995	<0.010	0.000
Weibull	9.771	<0.010	
3-Parameter Weibull	1.348	<0.005	0.000
Smallest Extreme Value	33.861	<0.010	
Largest Extreme Value	1.356	<0.010	
Gamma	0.415	>0.250	
3-Parameter Gamma	0.203	*	0.005
Logistic	1.777	<0.005	
Loglogistic	0.551	0.113	
3-Parameter Loglogistic	0.599	*	0.463
Johnson Transformation	0.139	0.975	

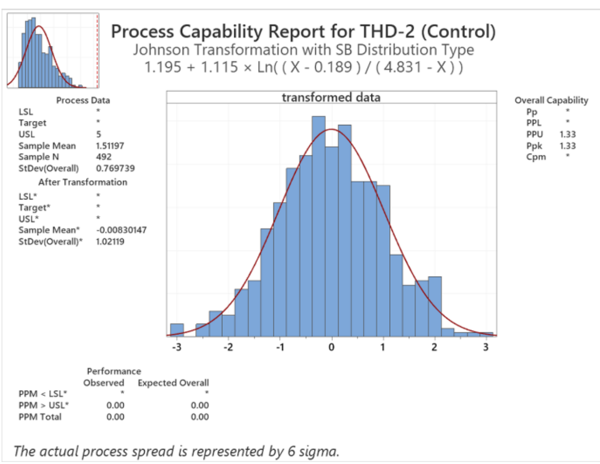


Appendix P– Process Capability Analysis of THD-2 (Control; Acrylate-Based UV Adhesive) Parameter

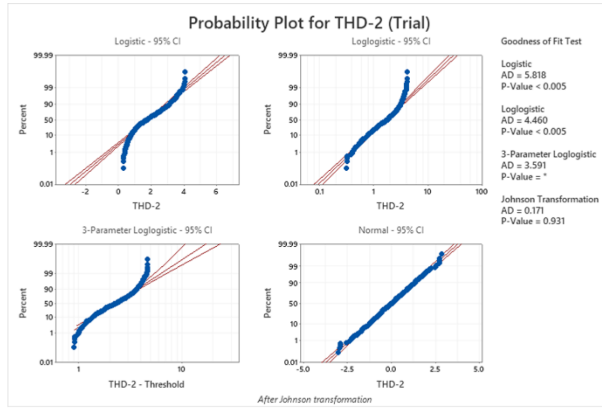


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	7.183	<0.005	
Box-Cox Transformation	0.772	0.045	
Lognormal	1.292	<0.005	
3-Parameter Lognormal	0.972	*	0.040
Exponential	54.558	<0.003	
2-Parameter Exponential	24.838	<0.010	0.000
Weibull	2.140	<0.010	
3-Parameter Weibull	0.385	0.418	0.000
Smallest Extreme Value	18.988	<0.010	
Largest Extreme Value	1.567	<0.010	
Gamma	0.851	0.032	
3-Parameter Gamma	0.529	*	0.014
Logistic	5.931	<0.005	
Loglogistic	1.779	<0.005	
3-Parameter Loglogistic	1.737	*	0.710
Johnson Transformation	0.173	0.928	

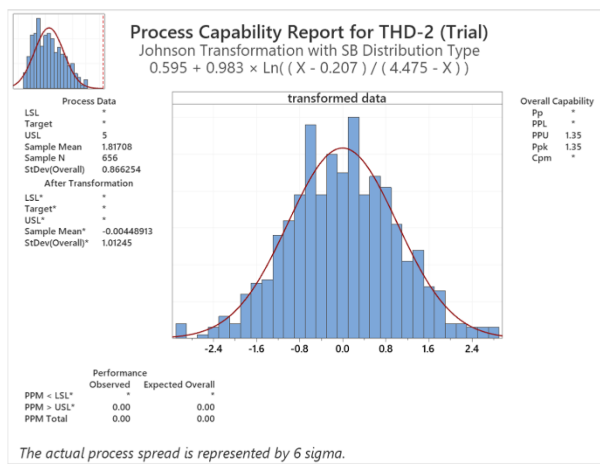


Appendix Q– Process Capability Analysis of THD-2 (Trial; Epoxy-Based UV Adhesive) Parameter

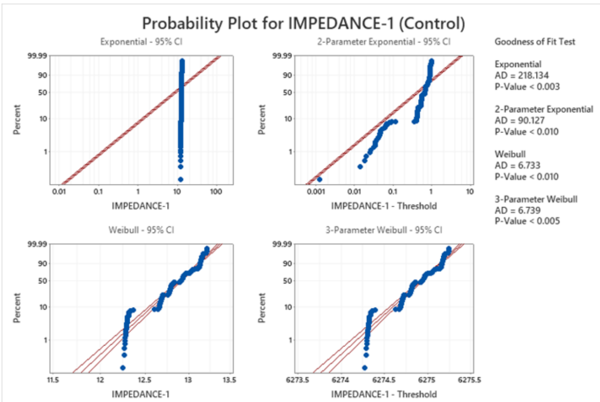


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	5.649	<0.005	
Box-Cox Transformation	1.908	<0.005	
Lognormal	4.436	<0.005	
3-Parameter Lognormal	2.407	*	0.000
Exponential	77.339	<0.003	
2-Parameter Exponential	44.063	<0.010	0.000
Weibull	1.761	<0.010	
3-Parameter Weibull	1.167	0.005	0.000
Smallest Extreme Value	15.738	<0.010	
Largest Extreme Value	2.611	<0.010	
Gamma	1.930	<0.005	
3-Parameter Gamma	1.945	*	0.844
Logistic	5.818	<0.005	
Loglogistic	4.460	<0.005	
3-Parameter Loglogistic	3.591	*	0.004
Johnson Transformation	0.171	0.931	

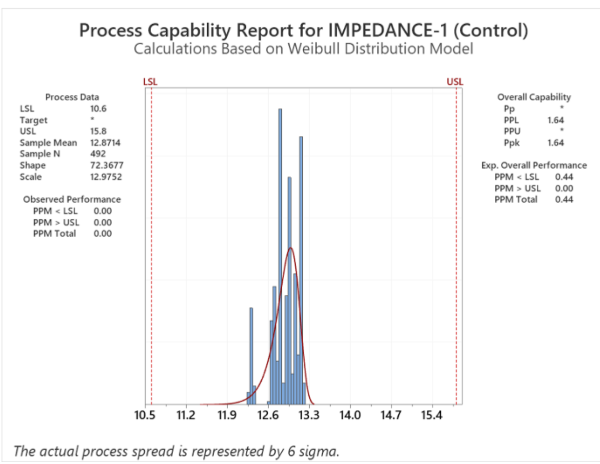


Appendix R– Process Capability Analysis of IMPEDANCE-1 (Control; Acrylate-Based UV Adhesive) Parameter

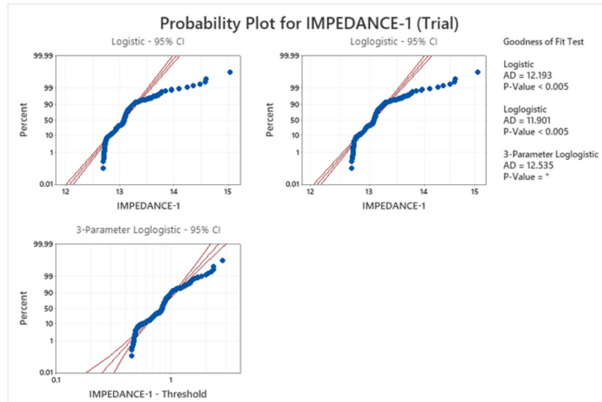


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	11.626	<0.005	
Box-Cox Transformation	9.342	<0.005	
Lognormal	12.311	<0.005	
3-Parameter Lognormal	11.630	*	0.004
Exponential	218.134	<0.003	
2-Parameter Exponential	90.127	<0.010	0.000
Weibull	6.733	<0.010	
3-Parameter Weibull	6.739	<0.005	0.332
Smallest Extreme Value	6.739	<0.010	
Largest Extreme Value	29.091	<0.010	
Gamma	12.080	<0.005	
3-Parameter Gamma	13.193	*	1.000
Logistic	8.227	<0.005	
Loglogistic	8.513	<0.005	
3-Parameter Loglogistic	8.228	*	0.025

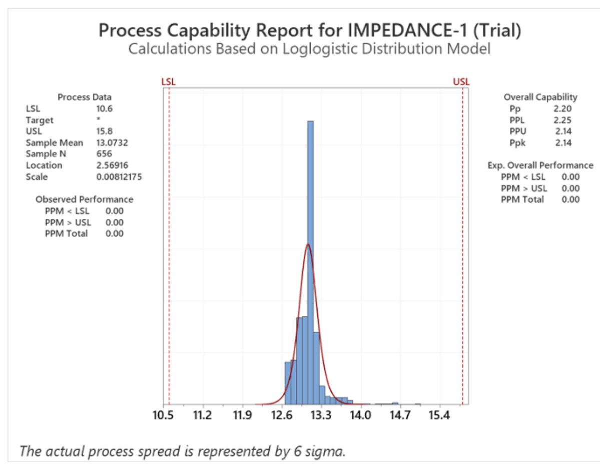


Appendix S– Process Capability Analysis of IMPEDANCE-1 (Trial; Epoxy-Based UV Adhesive) Parameter

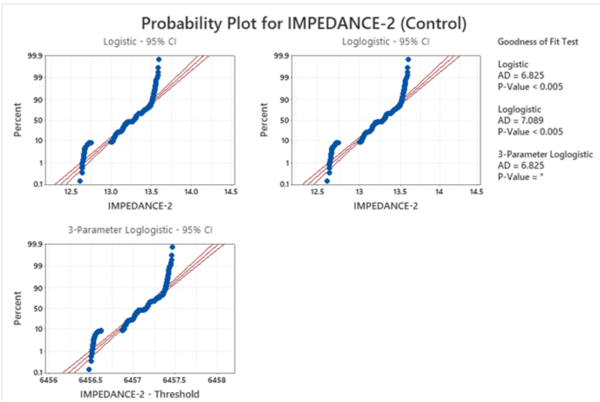


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	31.364	<0.005	
Box-Cox Transformation	20.990	<0.005	
Lognormal	29.090	<0.005	
3-Parameter Lognormal	19.216	*	0.000
Exponential	292.245	<0.003	
2-Parameter Exponential	76.925	<0.010	0.000
Weibull	95.267	<0.010	
3-Parameter Weibull	26.705	<0.005	0.000
Smallest Extreme Value	100.835	<0.010	
Largest Extreme Value	19.605	<0.010	
Gamma	29.779	<0.005	
3-Parameter Gamma	20.576	*	0.000
Logistic	12.193	<0.005	
Loglogistic	11.901	<0.005	
3-Parameter Loglogistic	12.535	*	0.000

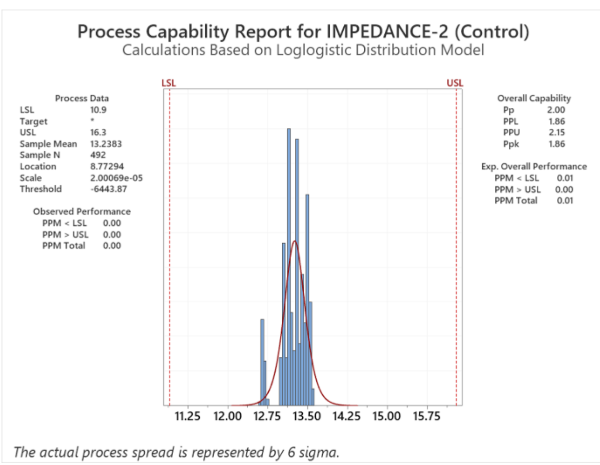


Appendix T– Process Capability Analysis of IMPEDANCE-2 (Control; Acrylate-Based UV Adhesive) Parameter

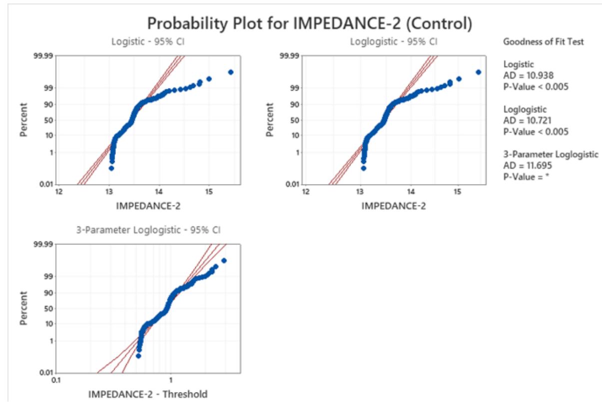


Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	9.736	<0.005	
Box-Cox Transformation	7.637	<0.005	
Lognormal	10.366	<0.005	
3-Parameter Lognormal	9.739	*	0.005
Exponential	218.236	<0.003	
2-Parameter Exponential	90.109	<0.010	0.000
Weibull	5.158	<0.010	
3-Parameter Weibull	5.170	<0.005	0.443
Smallest Extreme Value	5.170	<0.010	
Largest Extreme Value	26.668	<0.010	
Gamma	10.153	<0.005	
3-Parameter Gamma	11.818	*	1.000
Logistic	6.825	<0.005	
Loglogistic	7.089	<0.005	
3-Parameter Loglogistic	6.825	*	0.032

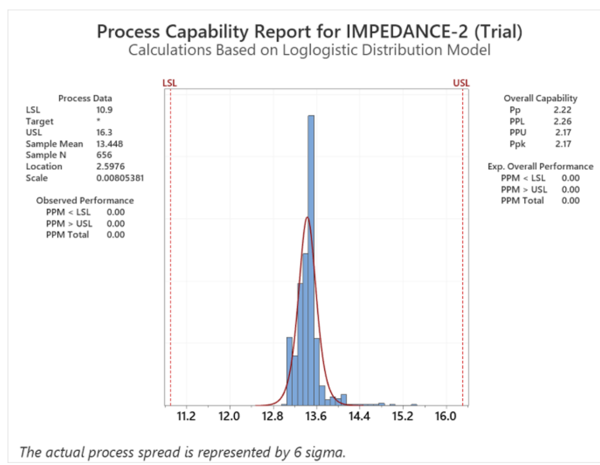


Appendix U– Process Capability Analysis of IMPEDANCE-2 (Trial; Epoxy-Based UV Adhesive) Parameter



Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	28.267	<0.005	
Box-Cox Transformation	19.108	<0.005	
Lognormal	26.225	<0.005	
3-Parameter Lognormal	18.225	*	0.000
Exponential	292.337	<0.003	
2-Parameter Exponential	79.123	<0.010	0.000
Weibull	92.187	<0.010	
3-Parameter Weibull	25.364	<0.005	0.000
Smallest Extreme Value	97.779	<0.010	
Largest Extreme Value	19.222	<0.010	
Gamma	26.839	<0.005	
3-Parameter Gamma	19.364	*	0.000
Logistic	10.938	<0.005	
Loglogistic	10.721	<0.005	
3-Parameter Loglogistic	11.695	*	0.000



Appendix V– Process Parameters for Drive Rod Adhesive Application and Curing Station

Parameters	Description
Dispense Pressure (MPa)	in Mpa; the pressure at the plunger
Dispense Time (s)	in seconds; the time the pressure is applied at the plunger
Needle Diameter (gauge)	the diameter of the needle used to dispense the UV adhesive
Irradiation Time (s)	the time the UV cement is exposed to the 365nm flood type with a minimum intensity of 1.67W/cm² and a maximum intensity of 4.17W/cm²
Adhesive Amount (mg)	in mg; the resulting weight of the dispense pressure x dispense time

Appendix W– DOE plan to identify the correct Dispense Pressure (MPa) and Dispense Time (sec)

	Factors	**Levels**			
Process Input Parameters	Dispense Pressure (MPa)	constant @ 0.2MPa			
	Dispense Time (s)	4 levels			
		level 1	level 2	level 3	level 4
		0.05 s	0.1 s	0.2 s	0.3 s
	Needle Diameter (gauge)	2 levels			
		level 1		level 2	
		32 gauge		34 gauge	

	Responses	**Levels**			**Target**
Process Output Variables	Pullout Data (N)	numeric			maximize
	Coverage	3 levels			0 (sufficient coverage)
		level 1	level 2	level 3	
		-1 (insufficient adhesive coverage)	0 (sufficient adhesive coverage)	1 (excessive adhesive coverage)	

Appendix X– DOE results: General Factorial Regression

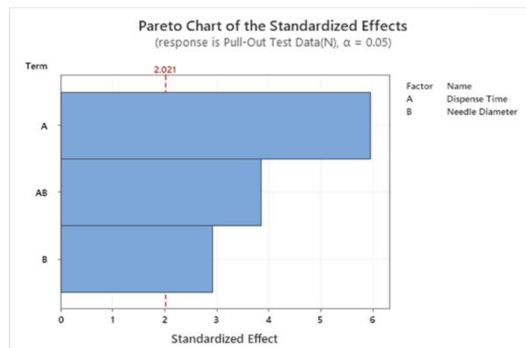
Factor Information

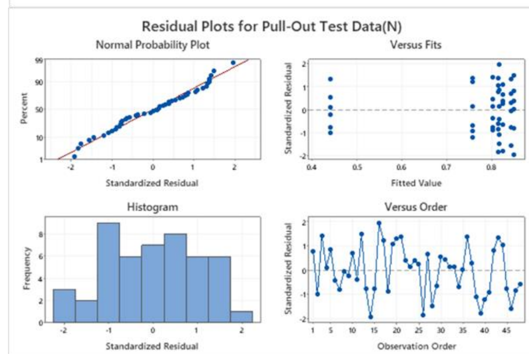
Factor	Levels	Values
Dispense Time	4	0.05, 0.10, 0.20, 0.30
Needle Diameter	2	32, 34

Analysis of Variance

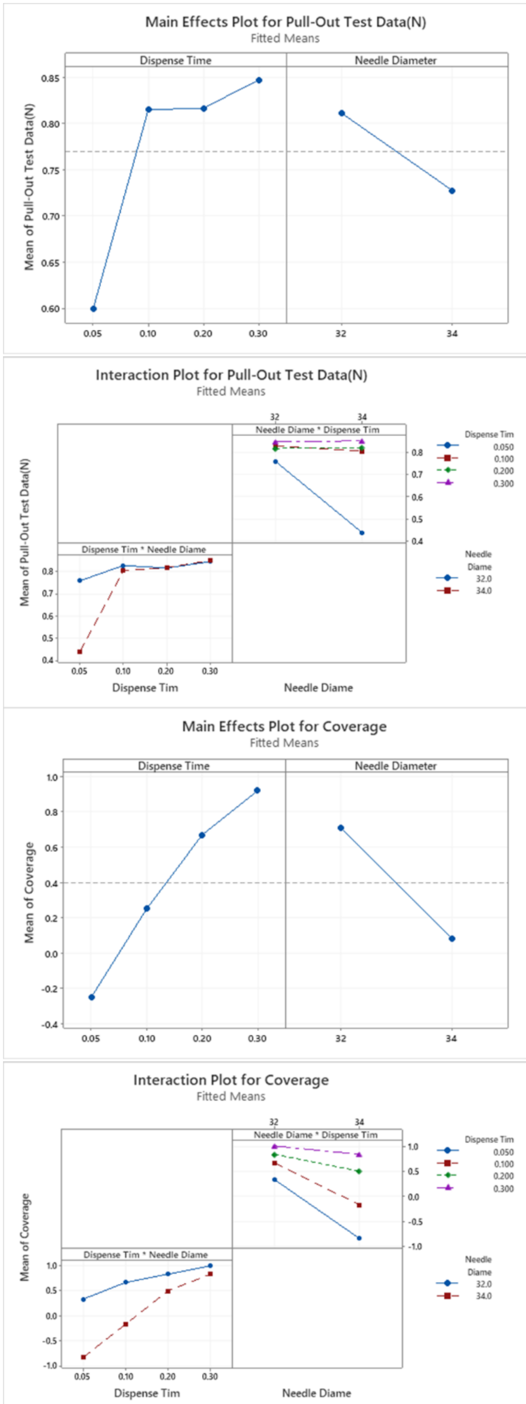
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Model	7	0.77786	66.46%	0.77786	0.111122	11.32
Linear	4	0.55619	47.52%	0.55619	0.139048	14.17
Dispense Time	3	0.47203	40.33%	0.47203	0.157342	16.03
Needle Diameter	1	0.08417	7.19%	0.08417	0.084169	8.58
2-Way Interactions	3	0.22166	18.94%	0.22166	0.073887	7.53
Dispense Time*Needle Diameter	3	0.22166	18.94%	0.22166	0.073887	7.53
Error	40	0.39259	33.54%	0.39259	0.009815	
Total	47	1.17044	100.00%			

Source	P-Value
Model	0.000
Linear	0.000
Dispense Time	0.000
Needle Diameter	0.006
2-Way Interactions	0.000
Dispense Time*Needle Diameter	0.000
Error	
Total	





Appendix Y– DOE results: Factorial Plots for Coverage and Pullout Data



Appendix Z– DOE results: Response Optimization: Pull-Out Test Data(N), Coverage

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Pull-Out Test Data(N)	Maximum	0.35	0.995		1	1
Coverage	Target	-1.00	0.000	1	1	1

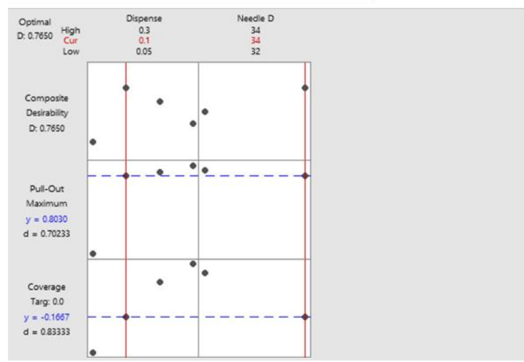
Solution

Solution	Dispense Time	Needle Diameter	Pull-Out Test Data(N) Fit	Coverage Fit	Composite Desirability
1	0.1	34	0.803	-0.166667	0.765030

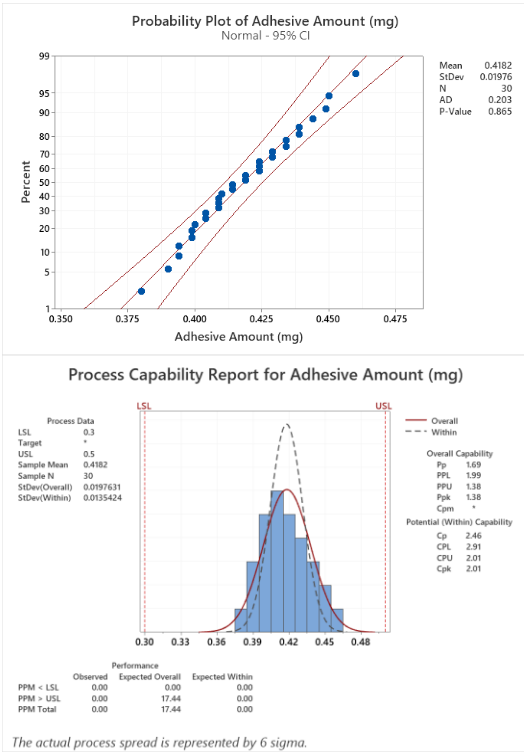
Multiple Response Prediction

Variable	Setting
Dispense Time	0.1
Needle Diameter	34

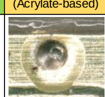
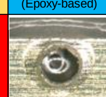
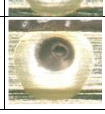
Response	Fit	SE Fit	95% CI	95% PI
Pull-Out Test Data(N)	0.8030	0.0404	(0.7213, 0.8847)	(0.5867, 1.0193)
Coverage	-0.167	0.177	(-0.524, 0.191)	(-1.112, 0.779)



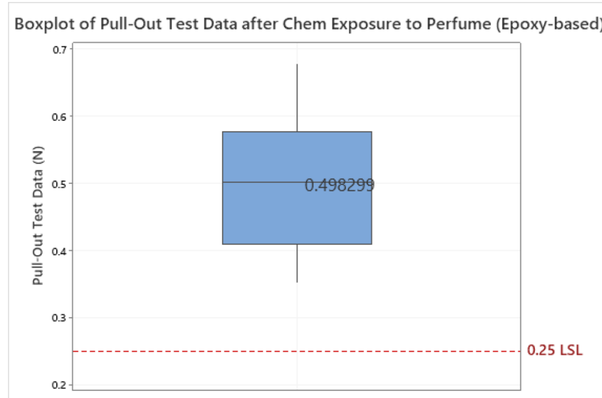
Appendix AA– Normality Test and Cpk of Adhesive amount (mg) based on Dispense time of 0.1s and 34-gauge Needle diameter.



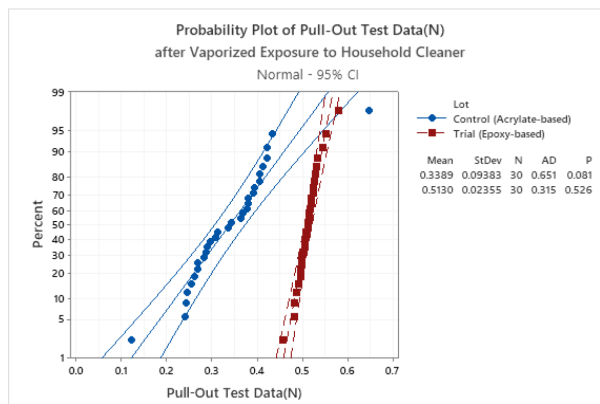
Appendix BB – Images of the Drive Rod to Diaphragm Adhesive Visual Condition Comparison after the Vaporized Chemical Exposure Tests

Drive Rod to Diaphragm Adhesive Visual Condition					
Test		Control Group (Acrylate-based)	Observations	Trial Group (Epoxy-based)	Observations
7	Vaporized Chemical Exposure Test		Minimal deterioration of the adhesive surface is visible; appearance is hazy and surface consistency is sticky.		The adhesive surface is not compromised, surface is still hard and well-bonded.
8	Vaporized Chemical Exposure + High Drive Stress Test		Minimal Deterioration of the adhesive is visible; appearance is hazy and its consistency is sticky.		The adhesive surface is not compromised, surface is still hard and well-bonded.
9	Low Temperature Storage + High Drive Stress Test		Minimal Deterioration of the adhesive is visible; appearance is hazy and its consistency is sticky.		The adhesive surface is not compromised, surface is still hard and well-bonded.
10	Vaporized Chemical Exposure Test + Low-Temperature Storage Test		Minimal Deterioration of the adhesive is visible; appearance is hazy and its consistency is sticky.		The adhesive surface is not compromised, surface is still hard and well-bonded.

Appendix CC – Boxplot of Drive Rod to Diaphragm Pull-out Test Data of Epoxy-Based UV-cured Adhesive after Chemical Exposure (Perfume)



Appendix DD – Normality Test of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive vs Epoxy-Based UV-cured Adhesive after Chemical Exposure (Household Cleaner)



Appendix EE– Test for Equal Variances of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive vs Epoxy-Based UV-cured Adhesive after Chemical Exposure (Household Cleaner)

Method

σ_1: standard deviation of Pull-Out Test Data(N) when Lot = Control (Acrylate-based)
σ_2: standard deviation of Pull-Out Test Data(N) when Lot = Trial (Epoxy-based)
Ratio: σ_1/σ_2
The Bonett and Levene's methods are valid for any continuous distribution.

Descriptive Statistics

Lot	N	StDev	Variance	95% CI for σ
Control (Acrylate-based)	30	0.094	0.009	(0.063, 0.148)
Trial (Epoxy-based)	30	0.024	0.001	(0.017, 0.035)

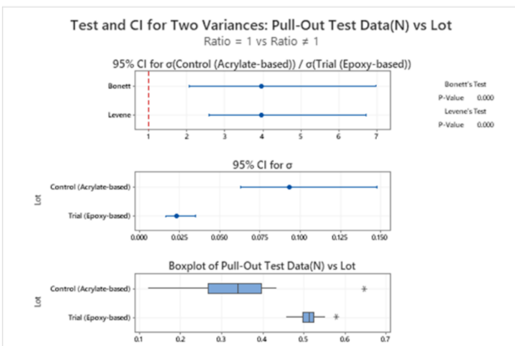
Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using Bonett	95% CI for Ratio using Levene
3.98440	(2.066, 7.003)	(2.611, 6.741)

Test

Null hypothesis H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level $\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
Bonett	12.14	1		0.000
Levene	23.21	1	58	0.000



Appendix FF– Test for Equal Means of Drive Rod to Diaphragm Pull-out Test Data of Acrylate-Based UV-cured Adhesive vs Epoxy-Based UV-cured Adhesive after Chemical exposure (Household Cleaner)

Method

μ_1: population mean of Pull-Out Test Data(N) when Lot = Control (Acrylate-based)
μ_2: population mean of Pull-Out Test Data(N) when Lot = Trial (Epoxy-based)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Pull-Out Test Data(N)

Lot	N	Mean	StDev	SE Mean
Control (Acrylate-based)	30	0.3389	0.0938	0.017
Trial (Epoxy-based)	30	0.5130	0.0236	0.0043

Estimation for Difference

Difference	95% CI for Difference
-0.1740	(-0.2100, -0.1381)

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
-9.85	32	0.000