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Enhancing Scrap Reduction in Electric Motor Manufacturing for the Automotive Industry: A Case Study Using the PDCA (Plan–Do–Check–Act) Approach

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Featured Application: The PDCA (Plan–Do–Check–Act) cycle, coupled with supplementary quality tools like 5W + 2H (Who, What, When, Where, Why, How, How much), three-legged five-why analysis, control charts, and capability analysis, serves as a potent strategy in the automotive sector for scrap reduction.

Abstract: The automotive industry is increasingly focused on waste management, elimination, and reduction to achieve sustainability and cost reduction. This focus drives the industry towards resource-efficient operations that minimize environmental impact while exceeding customer expectations. Meeting these demands necessitates the adoption of more efficient production methodologies, such as the PDCA cycle. This work presents a case study that illustrates the application of the PDCA methodology to minimize scrap generation due to process variability in a multinational company that manufactures electric motors for the automotive industry. The aim was to demonstrate how the PDCA methodology can improve quality standards by minimizing scrap generated during the manufacture of electrical armatures. Notably, the organization in this case study set a waste target of 0.7%, which was significantly exceeded. Finally, the implementation of this methodology can deliver significant economic benefits, with a total annual cost reduction of approximately USD 135,000.

Keywords: plan–do–check–act (PDCA); scrap; quality tools

1. Introduction

The management and disposal of waste presents a significant and growing challenge, particularly in densely populated areas of developed nations. Managing municipal solid waste (MSW) collection and disposal remains one of the major challenges facing urban environments globally [1]. Waste reduction should be a key objective for all companies seeking to achieve sustainability and minimize costs. This imperative has grown more pronounced amid increasingly stringent market demands. Today's customers expect tailored, high-quality products and services delivered swiftly and consistently. To meet these demands, companies are increasingly focusing on resource-efficient operations that minimize environmental impact while still surpassing customer expectations [2]. Meeting these evolving demands requires the adoption of more flexible production processes as well. The elimination of non-value-adding activities within the production workflows is essential for realizing this objective [3–5]. The automotive sector has been at the forefront of developing and deploying tools to pinpoint, analyze, and mitigate factors that could lead to competitive disadvantages [6].

This case study illustrates the application of the PDCA methodology to minimize scrap generation resulting from process variability in a multinational company engaged in the manufacture of electric motors for the automotive industry. Variations within the "armature" subassembly, which involve lamination, epoxy coating, and magnetic wire winding (Figures 1–3), were examined. Throughout the period from January to September 2022, an average scrap rate of 2.92% was identified from a total production output of 1,173,538 units. Figure 4 depicts the monthly scrap data documented by the company during this timeframe.

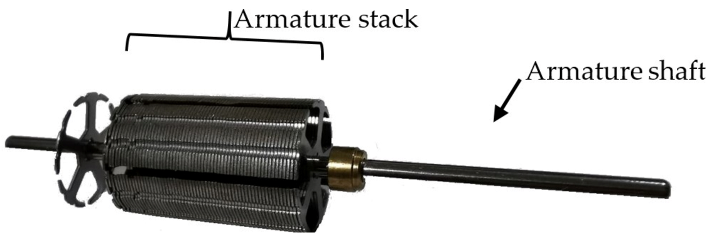


Figure 1. Lamination sub-process.

Figure 2. Epoxy coating addition sub-process.

Figure 3. Sub-process of magnetic wire winding.

Figure 4. Scrap per month (January–August 2022).

2. Literature Review

2.1. Understanding the PDCA Methodology: Core Principles and Applications

The PDCA methodology is a well-established and widely used tool for continuous improvements. Its origin can be traced back to Dr. W. Edwards Deming's lecture in Japan in 1950. However, Walther Shewhart had previously applied the scientific method in 1939 using his own three-phase cycle, namely specification–production–inspection. Dr. Deming further developed this concept in 1950, proposing a cycle that included design, production, market launch, market testing, and product redesign. The Japanese interpretation of Dr. Deming's "Deming wheel" during his 1950 and 1951 lectures ultimately led to the creation of the PDCA cycle as we know it today [7]. The PDCA cycle, a graphical representation of the eponymous methodology, has been used since then as a dynamic model focused on achieving customer satisfaction and supports quality improvement through four distinct phases, namely plan, do, check, and act [8]. It makes use of statistical and administrative tools to tangibly improve the performance of a company's processes, products, and services [9]. At its essence, PDCA entails developing a detailed action plan that outlines specific objectives and anticipates potential challenges. The "Do" phase involves executing planned actions, followed by a comprehensive assessment of outcomes in the "Check" phase. If the results prove favorable, the "Act" phase requires permanent integration of the changes into the process, with an ongoing emphasis on further refinement [10]. These attributes make the PDCA cycle a valuable tool for diverse industries, particularly the demanding automotive sector, where systematic approaches to boost productivity are crucial [11].

2.2. PDCA's Synergy with Quality Tools and Continuous Improvement Initiatives

PDCA demonstrates remarkable synergy with various tools and methodologies designed for continuous improvement. Its adaptable nature enables it to function as a core framework for complex methodologies or to complement other approaches within hybrid models [12–16]. This section highlights the efficacy of PDCA when combined with other tools through the following specific examples:

- Scrap reduction: Studies like those conducted by Amaral et al. [17] demonstrate the successful application of PDCA alongside a SIPOC (Suppliers, Inputs, Process, Outputs, Customers) matrix, chart control, 5S (Sort, Straighten, Shine, Standardize, Sustain), and visual management in an automotive electromechanical component manufacturer. This implementation led to significant waste reduction through improved quality and productivity. Additionally, Silva et al. [18] demonstrated its practical application in minimizing can loss within a beverage company, ultimately resulting in significant waste reduction through improved quality and productivity.
- Process optimization: Research by Singh Sidhu et al. [19] and Tahiduzzaman et al. [20] highlights the role of PDCA in implementing 5S and other lean tools within agricultural and manufacturing contexts, ultimately leading to decreased cycle time and increased profitability.
- Environmental management: Garza-Reyes et al. [21] proposed utilizing PDCA for systematic implementation of environmental VSM (value stream mapping) studies, while Goyal et al. [22] reported a case study employing Kaizen and PDCA to reduce material waste.
- Defect reduction: Isniah et al.'s research [23] focused on reviewing existing literature from 2015 to 2020 on the use of the PDCA cycle as a tool for improvement in organizations. This study showed that a total of 16% of all references found are related to defect reduction, using the PDCA cycle in conjunction with other tools such as KAIZEN, seven basic statistical tools, statistical process control, and PFMEA (Process Failure Mode Effect Analysis).

The literature in this field also highlights that, despite the effectiveness that the PDCA cycle has demonstrated in improving organizational operations, there is still a lack of knowledge about how to apply it to obtain competitive advantages [24,25].

2.3. Variations of the PDCA Cycle

One of the versions of the PDCA cycle is PDSA (Plan, Do, Study, Act). PDCA is used for more straightforward improvement scenarios, and PDSA is applied in more complex scenarios—when the metrics being checked and the environmental conditions surrounding those metrics require more extensive reflection [9,26,27]. Another version of the PDCA cycle is OPDCA (Observe, Plan, Do, Check, Act). The added "O" stands for observation or, as some versions say, "Grasp the current condition". The emphasis on observation and the current condition is very important in lean manufacturing/the Toyota Production System [28]. The next version is EPACA (Evaluate, Plan, Action, Check, Amend). This approach stresses that the most significant organizational improvements are achieved by effectively implementing corrective and preventive actions [26]. Finally, PDAC (Plan, Do, Act, Challenge) is an advanced form of the PDCA cycle directed at taking on new challenges in the scope of improvement of the organization by setting ambitious goals [26].

2.4. PDCA Integration with Quality Management Systems

The popularity of the PDCA cycle extends beyond other improvement methodologies; it is deeply ingrained in most major quality management systems. Standards such as ISO (International Organization for Standardization) 9001, ISO 14001, and ISO 45001 have readily embraced and integrated it. This section explores the integration of PDCA within various quality management systems, as follows [29–31]:

- ISO 9001: The ISO 9001:2015 standard [32] leverages the PDCA cycle to illustrate how its clauses 4 to 10 can be systematically grouped and implemented (Figure 5). This serves as a powerful testament to the PDCA cycle's effectiveness and versatility in driving continuous improvement within quality management systems [33–35].
- Adaptability: Research by Chiarini and Cherafi [36] demonstrated this adaptability by developing an implementation guideline for manufacturing companies. This guideline, rooted in the PDCA model, effectively integrates ISO 9001 requirements with Industry 4.0 technologies. It showcases how PDCA can bridge the gap between established quality management systems and the latest technological advancements.
- Service industry: Habibie and Kresiani [28] meticulously analyzed the ISO/IEC (International Electrotechnical Commission) 17025:2017 standard clause by clause, exploring its connection to the PDCA concept within the process approach framework. Their findings suggest that ISO/IEC 17025:2017 incorporates the principles of the PDCA model. The standard's specific clauses address each stage within the overall framework of a laboratory's quality management system (Figure 6).
- IATF (International Automotive Task Force) 16949: This standard requires organizations to have a documented problem-solving process to prevent recurrence in clause 10.2.3. Subclause c) of this clause specifies that this includes root cause analysis, the methodology used, analysis, and results [37]. The 8Ds technique is documented in the literature as a widely accepted technique for meeting this requirement [38,39]. The PDCA cycle has served as a reference due to its strong relationship with the 8Ds, as it has functioned as an advanced approach to decision-making and problem-solving [40,41].

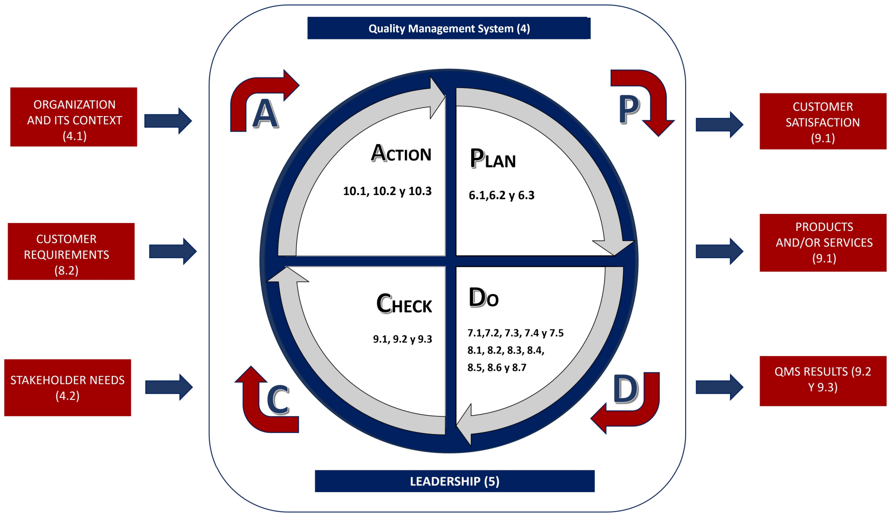


Figure 5. Representation of the ISO 9001:2015 structure in the PDCA cycle.

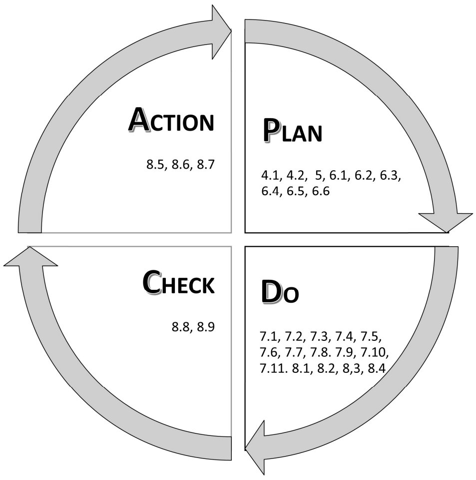


Figure 6. Mapping of ISO/IEC 17025:2017 clauses to the PDCA cycle for quality management in laboratories.

2.5. Hipot (High-Potential) Failures in Electric Armatures

Hipot testing is a crucial quality control procedure for electric armatures, ensuring their ability to withstand operational voltage stresses without breakdown. However, failures during hipot tests can be costly and time-consuming, requiring root cause analysis and corrective actions. This section reviews recent research on failures encountered during hipot testing of electric armatures.

- Partial discharge (PD) activity: PDs are localized dielectric breakdowns within the insulation system, often indicated by increased current leakage during hipot tests. Chai et al. [42] explored the use of advanced PD detection techniques to identify and locate PD sources in electric motor stator windings, aiding in early failure prediction. Diab et al. [43] provided detailed experimental specifications involving PD measurements methods and PD data post-processing Algorithms. The obtained results are drawn as a useful and timely reference that enhances the understanding of the insulation PD process in SiC (silicon-carbide)-based power electronics applications.
- Automated hipot failure detection: Research by Agnes [44] introduced a new concept developed for high-voltage testing in electrical apparatus used in railway systems, which supports predictive maintenance. This device conducts insulation tests between contacts and the ground wherein contacts must withstand the test voltage for a speci-

fied time; it also tests several apparatus at the same time, improving efficiency in the maintenance sector.

- Moisture ingress: Moisture absorption in the insulation degrades its dielectric properties and increases the risk of hipot test failures. Ghani et al. [45] examined the effect of moisture content on the breakdown strength of stator coil insulation under various temperatures.
- Advanced detection and mitigation techniques: Recent research has focused on developing advanced methods for detecting and mitigating hipot test failures in electric armatures. These include (a) non-destructive testing (NDT) techniques. Research by Nageshwar et al. [46] reviewed the main aging and failure mechanisms of stator winding and methods for extending the useful life of the machine. The symptoms of each failure mechanism were discussed, and an overview of various electrical diagnostic techniques for condition assessment of stator winding insulation was presented. (b) Machine Learning for Anomaly Detection. Research by Ferras et al. [47] explored the application of machine learning algorithms to data for different possible types of anomalies in electric motors, such as uncoupled, overloaded, unbalanced, misaligned, and normal anomalies. The obtained results show how these algorithms can be effective in classifying the different types of anomalies and that the two models that presented the best accuracy values were k-nearest neighbor and multi-layer perceptron.

3. Research Design

The focal point of this research is to address the reduction in scrap generated during hipot testing within the subassembly manufacturing process of electric motors. The hipot test, conducted on site, involves subjecting the magnetic wire winding to a high-voltage withstand test. The primary objective of this test is to detect any weak insulation points [48]. During the test, an exceptionally high-voltage charge, surpassing the normal operating voltage, is applied between the conductors and their insulation. The examination tracks the leakage current flowing through the insulation, essentially assessing the product's ability to endure high-voltage stresses safely. Any insulation leakage triggers an alarm at the armature-level hipot tester, indicating improper continuity, a situation that should not occur. Therefore, it is imperative to identify the root causes of defects originating from this testing phase. It is essential to isolate the factor or combination of factors responsible for these defects; these can be found in the following sub-processes:

- Lamination: This sub-process is responsible for generating the armature body, which is made of 60 layers of steel material called laminations. This number of laminations can vary until enough are stacked to achieve the armature stack length specification (Figure 1). Each lamination comes to the company under study from a stamping process performed by an external supplier. The first and last laminations that make up the armature are the same as the rest that are in the middle of them. For the union between the laminations to the shaft, a pressing device is used that introduced a shaft under pressure in the center of the laminations, which have a star-shaped cut, achieving a tight fit. For additional fixation, the device then makes a rivet on both sides of the laminations' center at the end of the process.
- Epoxy coating: This sub-process is responsible for generating electrical insulation by applying an epoxy resin in powder form along the entire interior of the armature body, covering from the first lamination to the last. Then, through a curing process, the powder is heated to form a solid layer (Figure 2).
- Wire winding: This sub-process involves a continuous series of winding from each bar on the commutator, which loops around the stack teeth and connects to the next bar on the commutator, using the stack slots to insert the wire winding from one side of the armature to the other (Figures 2 and 3). It is in this winding that the magnetic fields are generated for the speed that the motor will have. To perform this operation, an automatic winding machine is used in which the operator prepares the correct

cable sizes and coil heads. Afterward, only the required dimensions and the number of turns need to be entered into the machine's computer; the rest of the process is automatic (Figure 3).

Ultimately, this study aims to improve quality standards by minimizing scrap generated during armature manufacturing. The selected methodology, guided by the application of PDCA for defect and rejection reduction [49–51], consists of the following four primary steps:

- Literature review: This phase involved analyzing published articles featuring case studies demonstrating the PDCA cycle in practice, as well as examining the individual PDCA phases, exploring the interconnections between PDCA and other improvement methodologies, and investigating its relationships with quality management systems.
- Case study development: This stage focused on constructing the specific case relevant for this research study.
- Results analysis: Following the implementation of the PDCA cycle, the obtained results were exhaustively analyzed.
- Conclusions and recommendations: Based on the findings, concrete conclusions were formulated, and practical recommendations for further improvement were provided.

4. Case Study

The following subsection describes the methodology applied in the present case study.

4.1. The Method Employed in this Study Is Illustrated in Figure 7

The present study used the PDCA cycle, which consists of the following four phases: (1) plan, (2) do, (3) check, and (4) act. The following subsections elaborate how each PDCA phase was applied in this study.

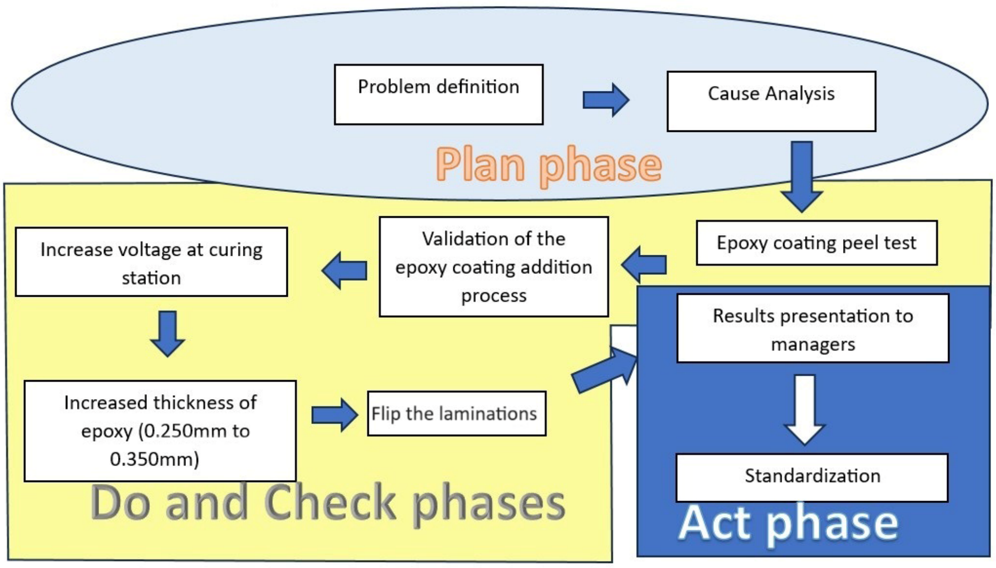


Figure 7. Research method.

4.1.1. Phase 1: Plan

In this phase, the problem definition was defined using the 5W + 2H approach. Table 1 presents the obtained information.

Table 1. Aspects of the company's current situation were categorized according to the 5W + 2H approach.

PDCA Quick Response

Problem description by customer/location of the problem: During hipot testing, armatures fail due to cable contact with laminations when windings are introduced. This creates continuity between the cable and metal part.
What is the problem? > Use 5W + 2H to determine the current situation (C/S).
Customer view

- What happened? The hipot test armature fails due to cable contact with the lamination during winding, likely caused by sharp lamination edges and damaging the cable.
- Why is it a problem?

1. Customer impact: engine inoperative;
2. Logistic impact: missed customer demand;
3. Impact on part assembly: poor performance;
4. Technical impact: armature non-compliance with hipot values;
5. Reliability impact: armatures fail to meet standards;
6. Severity: potential short circuit and motor burnout due to induced current.

- When did it start? The issue began in January 2022 and persisted to September 2022.
- Who detected it? The issue was detected by a certified hipot station operator.
- Where was it detected? The issue was detected at the hipot tester station.
- How was it detected? The issue was detected through a machine alarm indicating failure to reach or exceed the test parameter values.
- How many defective parts? There were 1,173,538 defective pieces identified from January to September 2022.

Company View

- What is the difference between defective and non-defective parts?

The difference between defective and non-defective parts is as follows:
Non-defective part: Successfully completes the hipot test without triggering any alarms. The cable does not come into contact with the laminations during the test.
Defective part: Fails hipot test, triggering an alarm. The cable makes contact with the laminations during the test, leading to failure indication.

- Were the parts produced in the standard process? Yes, the parts were manufactured according to the standard process.
- When were they manufactured by the company? The parts were manufactured from January to September 2022.
- Who made it? The data regarding the manufacturer are not provided in this article due to confidentiality reasons.
- Other applications: The parts were not used in any other applications.
- Defect detection: The defect occurred during the normal process at the hipot testing station.
- Previous occurrences: This particular failure mode has not been reported previously, either internally by the company or by customers.

Based on the information in Table 1, the problem of continuity between the winding and metal likely stems from a multifactorial issue. All factors ultimately converge on the presence of an undesirable direct connection, typically due to insulation failure. This failure can be attributed to various factors, notably the inadvertent insertion of the wire into the epoxy coating during the winding process, leading to contact with the laminate. The lamination itself features a sharp edge that damages the cable, further facilitating this contact. For visual reference, please see the magnified image of defective and non-defective parts in Figure 8.

Table 2 outlines the application of the three-legged five-why analysis method, which facilitated a comprehensive investigation into the root causes of the error. This approach enabled the study to explore three distinct perspectives—specifics, detection, and systemic issues—in order to gain a thorough understanding of the underlying cause surrounding the error.

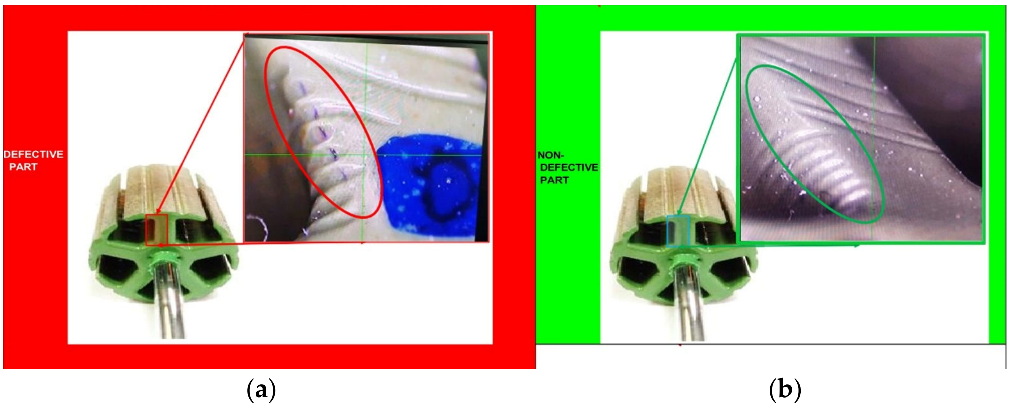


Figure 8. Examples of (**a**) defective and (**b**) non-defective parts.

Table 2. Three-legged five-why analysis.

Issue Description:
The production line for the armature subassembly came to a halt due to failures in the hi-pot tests.
Details: During the specific process of checking armature resistance and varistor function and conducting a hipot test, the machine triggered the alarm due to a detected defective part, prompting a subsequent investigation.
The high-potential tester's alarm blared, alerting operators of a part that failed the crucial insulation test.
Why?
The high-potential test detected unintended leakage current, indicating a direct electrical path between the armature cable and the laminated core.
Why?
The stress event compromised the epoxy coating, leading to a breach in cable insulation and contact with the lamination.
Why?
Non-uniform coating distribution during the manufacturing process resulted in a significant decrease in epoxy thickness on the lamination walls.
ROOT CAUSE
Non-uniform coating distribution during the manufacturing process led to a significant decrease in epoxy thickness on the lamination walls.
Detection
Why?
The tester measured a detachment force (the resistance to peeling), falling within the acceptable range with a minimum value of 58.8399 N (6 kgf).
Why?
For the adhesion test, the armature sample must be tilted to an angle between 80° and 90° from the vertical to simulate the stress conditions experienced by the cable during winding.
ROOT CAUSE
For the adhesion test, the armature sample must be tilted to an angle between 80° and 90° from the vertical to simulate the stress conditions experienced by the cable during winding.
Systemic
Why?
This failure mode was not identified as a potential risk in the PFMEA or addressed in the control plan.
ROOT CAUSE

The following conclusions were drawn from the first two phases of the proposed methodology:

(a) The armature production line frequently halts due to hipot issues, resulting in costly stoppages and the generation of scrap. Unwanted continuity in the pieces renders them unusable in electric motors, necessitating their disposal.
(b) Thin or uneven epoxy coating, crucial for preventing contact between the cable and lamination, is identified as a significant factor contributing to the hipot failures.
(c) The validation process for the epoxy coating addition process is deemed unreliable.

Given these findings, the "Do" phase should prioritize improvement strategies aimed at ensuring the insulation of the lamination and wire winding.

4.1.2. Phases 2 and 3: Do and Check

In phases 2 and 3, the focus is on implementing improvements and verifying their effectiveness. Key improvement opportunities to address the identified insulation breakdown between the cable and lamination include the following:

- Conducting peel strength analysis to assess the adhesive strength of the epoxy coating;
- Validating the epoxy coating addition process;
- Adjusting the voltage at the epoxy coating curing station to optimize curing conditions for better insulation;
- Testing different thicknesses of the epoxy coating to determine the optimal balance between insulation effectiveness and production efficiency;
- Evaluating the impact of rotating the lamination faces 180° on the compatibility of the armature body with the epoxy coating.

Additionally, a Differential Scanning Calorimetry (DSC) test was conducted to analyze the thermal behavior and curing properties of the epoxy coating, aiming to provide further process optimization efforts.

Epoxy Coating Peel Test

The epoxy coating peel test serves as a crucial element of process validation, assessing the additive strength of the epoxy coating to the laminated shell. It simulates the forces exerted by the cable during the winding process, offering insights into the coating's ability to resist detachment under real-world conditions. The test involves applying controlled tensile force to detach the epoxy coating from the laminations. This procedure is conducted using a specialized machine similar to the one depicted in Figure 9.

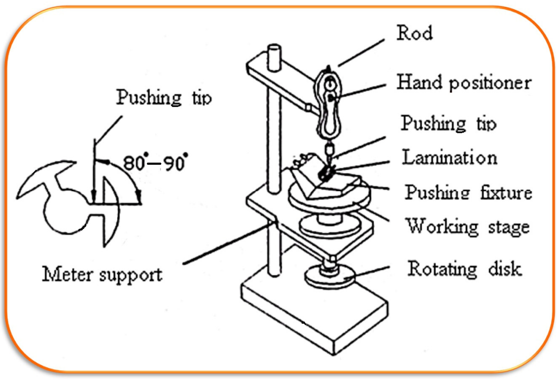
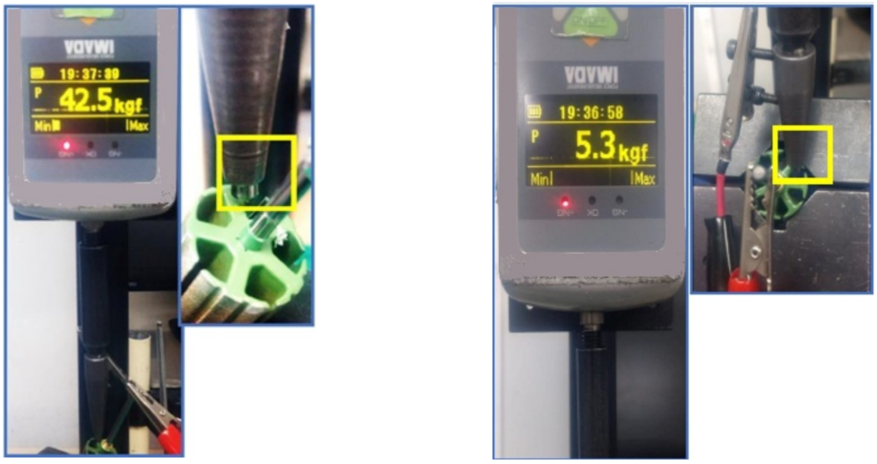


Figure 9. Machine for epoxy coating peel test.

The peel test specification stipulates a detachment force of 58.8399 N (6 kgf). However, conducting the test with the armature in a vertical position (Figure 10a) resulted in a significantly higher force of 416.78 N (42.5 kgf). Upon consulting with the company's headquarters in China, it was revealed that this vertical orientation was incorrect. They advised that the armature should be positioned at an angle between 80° and 90° during the test. This ensures the pushing tip contacts the most sensitive area, where the cable exerts the maximum force.



(**a**) (**b**)

Figure 10. (**a**) Force in vertical orientation for epoxy coating detachment; (**b**) peel strength of epoxy coating at 80°–90°.

Re-running the test with the armature tilted, as recommended, led to a dramatic decrease in detachment force for the same sample—from 416.78 N to 51.9752 N (42.5 kgf, to 5.3 kgf). This result clearly falls below the specified threshold (Figure 10b). The previously employed incorrect testing procedure likely explains why the epoxy coating exhibited increased susceptibility to cracking and chipping.

Validation of the Epoxy Coating Addition Process

To comprehensively validate the production process and ensure consistent output quality, a process parameter matrix was documented, encompassing all critical parameters for each phase (laminating and degreasing, cooling, epoxy addition, and cleaning). Table 3 details the specific parameters, as well as their maximum, minimum, and average values.

Table 3. Parameter matrix of production process phases.

	Transfer Time	**Laminating and Degreasing**				
Parameter	**Worm Gear Velocity**	**Voltage Across Heating Resistor**	**Resistor Temperature (Start)**	**Resistor Temperature (Middle)**	**Resistor Temperature (End)**	**Air Pressure**
Units	**rpm**	**kV**	**°C**	**°C**	**°C**	**kPa**
Max	15	2.7	33	129	202	0.55
Min	14.63	2.7	30	112	166	0.55
Average	14.68	2.7	32.14	123	187	0.55

	Epoxy addition						
Parameter	**Coat 1 Pressure**	**Coat 2 Pressure**	**Feeder Pressure**	**Vacuum Pressure**	**Guide Rail 1 Distance**	**Guide Rail 2 Distance**	**Electrostatic Box**
Units	**kPa**	**kPa**	**kPa**	**°C**	**mm**	**mm**	**kV**
Max	0.1	0.1	0.16	0.1	3.5	2	61
Min	0.06	0.06	0.14	0.1	3.5	2	61
Average	0.08	0.08	0.151	0.1	3.5	2	61

	Epoxy Addition	**Epoxy Curing**			
Parameter	**Water Pressure**	**Voltage Across Heating Resistor**	**Resistor Temperature (Start)**	**Resistor Temperature (Middle)**	**Resistor Temperature (End)**
Units	**kPa**	**kV**	**°C**	**°C**	**°C**
Max	0.4	3	39	212	272
Min	0.4	3	37	163	264
Average	0.4	3	38.28	192.14	271.42

Figure 11 illustrates the epoxy coating curing process for armatures, highlighting the critical temperature points through each phase.

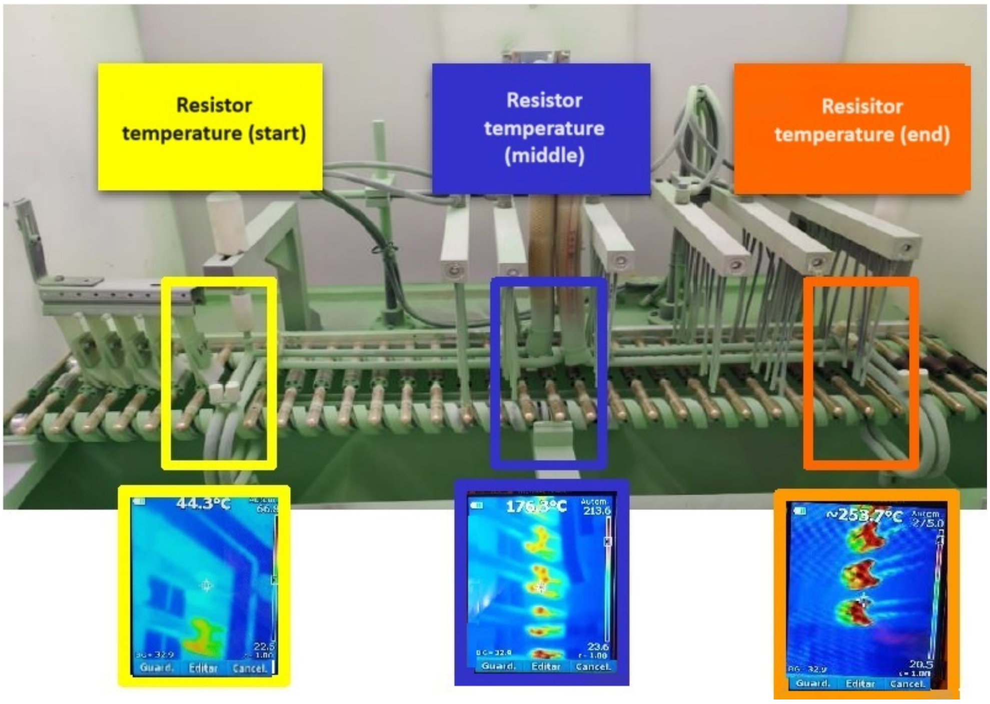


Figure 11. Epoxy curing station.

To identify potential areas for process improvements, an initial assessment was conducted. The assessment aimed to determine if the parameters listed in Table 3 exhibited statistical control over critical output characteristics at different process phases. Control charts were generated for individual measurements. Figures 12–15 demonstrate stable and predictable processor behavior for the laminating and degreasing and epoxy curing temperatures. Lines and dots in Figures 12–15 represent the following: central line ($\overline{X}$) represents the mean of the process data; each dot represents and individual data point collected from the process. Control limits (UCL—Upper Control Limit and LCL—Lower Control Limit) represent the statistically expected range of variation in the process. The absence of data points outside the control limits, trends or other patterns of statistical instability indicates consistent process performance. This stable foundation allows for the development of reliable improvement plans. [52].

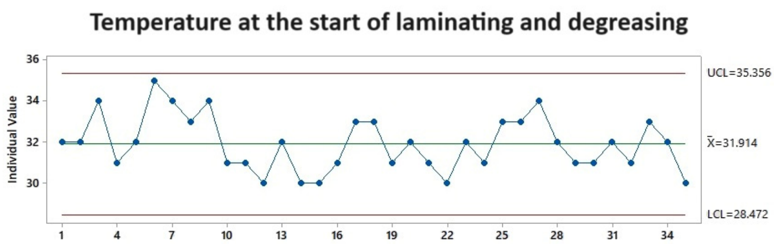


Figure 12. Individual control chart for armature temperature at the start of laminating and degreasing (in °C).

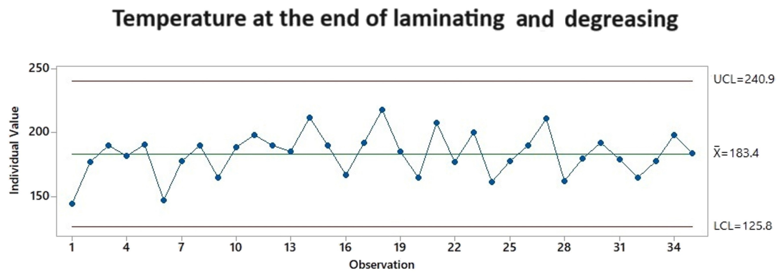


Figure 13. Individual control chart for armature temperature at the end of laminating and degreasing (in °C).

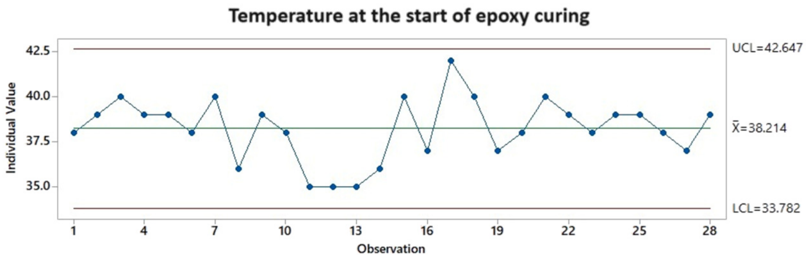


Figure 14. Individual control chart for armature temperature at the start of epoxy curing (in °C).

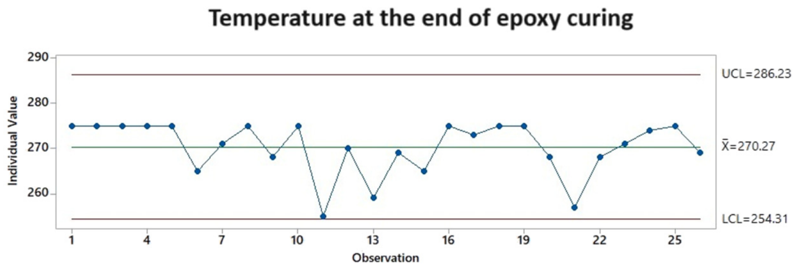


Figure 15. Individual control chart for armature temperature at the end of epoxy curing (in °C).

Additionally, process capability measures were obtained for critical output characteristics like epoxy thickness and detachment force from both sides of the armature. Figure 16 and Table 4 reveal high process capability in meeting epoxy thickness specifications, consistently achieving values within the 100–500 micron range. However, Figure 17 and Table 5 highlight a significant challenge, namely low process capability in meeting the 58.8399 N (6 kgf) specification for epoxy detachment force. This deficiency is particularly pronounced on the short side of the armature reinforcement (Figure 18).

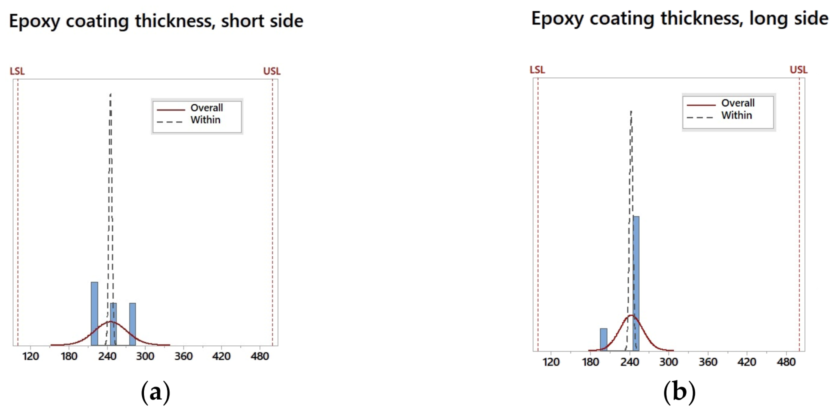
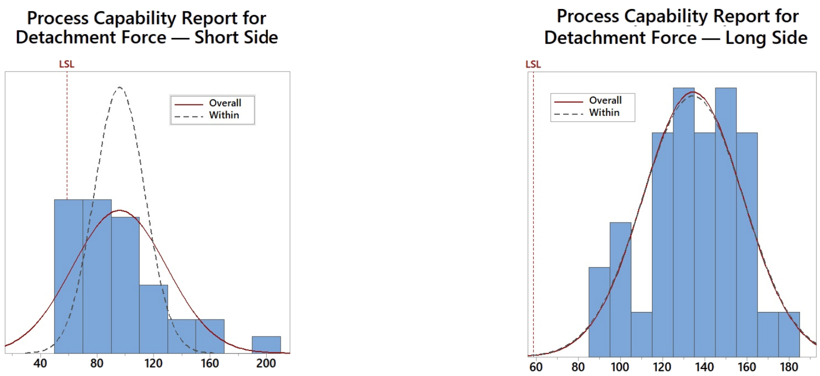


Figure 16. Process capability histograms for epoxy coating thickness: (**a**) short-side armature; (**b**) long-side armature.

Table 4. Process capability measures for epoxy coating thickness.

		Short-Side Armature			
Process Data:		**Overall Capability**		**Potential (Within) Capability**	
LSL (lower specification limit)	100	Pp	2.63	Cp	28.41
UPL (upper specification limit)	500	PPL	1.92	CPL	20.70
Sample mean	245.714	PPU	3.34	CPU	36.12
Sample N	35	Ppk	1.92	Cpk	20.70
Overall StDev (standard deviation)	25.3546				
StDev (within)	2.34668				
Performance:					
	Observed	Expected Overall		Expected Within	
PPM < LSL	0	0		0	
PPM > USL	0	0		0	
PPM total	0	0		0	
Long-Side Armature					
Process data:		Overall Capability		Potential (Within) Capability	
LSL (lower specification limit)	100	Pp	3.76	Cp	25.57
UPL (upper specification limit)	500	PPL	2.68	CPL	18.26
Sample mean	242.857	PPU	4.83	CPU	32.87
Sample N	35	Ppk	2.68	Cpk	18.26
Overall StDev (standard deviation)	17.7518				
StDev (within)	2.60743				
Performance:					
	Observed	Expected Overall		Expected Within	
PPM < LSL	0	0		0	
PPM > USL	0	0		0	
PPM total	0	0		0	



(**a**) (**b**)

Figure 17. Process capability histograms for epoxy detachment force: (**a**) short-side armature; (**b**) long-side armature.

Table 5. Process capability measures for epoxy detachment force.

Process Data:				**Overall Capability**		
	Short-Side Armature		**Long-Side Armature**		**Short-Side Armature**	**Long-Side Armature**
LSL	58.8399		58.8399	PPL	0.37	1.07
Sample mean	96.0496		134.436	Ppk	0.37	1.07
Sample N	35		35	Potential (within) capability		
Overall StDev	33.3546		23.6373	CPL	0.69	1.05
StDev (within)	17.9247		23.9849	Cpk	0.69	1.05
Performance:						
	Observed		Expected Overall		Expected Within	
	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature
PPM < LSL	0	0	132,301.04	691.52	18,952.24	811.29
Total PPM	0	0	132,301.04	691.52	18,952.24	811.29

Figure 18. The two sides of the armature.

Adjusting the Voltage at the Epoxy Coating Curing Station to Optimize Curing Conditions

To investigate the cause of low detachment force, two targeted experiments were conducted. In the first experiment, the voltage at the curing station was increased from 3 kV to 3.1 kV to explore whether enhanced curing could harden the epoxy and prevent cable penetration, a potential contributor to hipot failures. This test involved sampling 30 pieces, with separate detachment force measurements for both the short and long sides of the armature, referring to the rotation axis as defined in Figure 18. In the second experiment, the thickness of the epoxy coating was increased from 0.250 mm to 0.350 mm, aiming to provide a stronger physical barrier against cable abrasion. Again, detachment force was measured on both sides of a sample of 30 pieces.

Table 6 shows the results of a mean difference test for breaking force before and after the voltage change experiment in the curing station. The aim was to evaluate the following hypotheses:

H0. $\mu_{before\ voltage\ change} = \mu_{after\ voltage\ change}$.

H1. $\mu_{before\ voltage\ change} \neq \mu_{after\ voltage\ change}$.

Table 6. Mean difference test results for breaking force before and after increasing voltage in the curing station: (a) short-side armature; (b) long-side armature.

(a)					(b)				
	N	**Mean**	**StDev**	**SE Mean**		**N**	**Mean**	**StDev**	**SE Mean**
C9	35	96.0	33.4	5.6	C10	35	134.4	23.6	4.0
C11	30	58.5	28.0	5.1	C12	30	141.3	58.4	11
C9 = Data before 1st experiment					C10 = Data before 1st experiment				
C11 = Data after 1st experiment					C12 = Data after 1st experiment				
Difference = μ (C9)—μ (C11)					Difference = μ (C10)—μ (C12)				
Estimate for difference: 37.54					Estimate for difference: −6.9				
95% CI for difference: (22.31, 52.76)					95% CI for difference: (−30.0, 16.2)				
T-Test of difference = 0 (vs ≠)					T-Test of difference = 0 (vs ≠)				
T-Value = 4.93					T-Value = −0.61				
p-Value = 0.000 DF = 62					*p*-Value = 0.548 DF = 37				

The data considered for the statistical calculation (N in Table 6) were those obtained from the samples taken from the process before and after adjusting the voltage in the curing station. A significance level (α) of 0.05 was considered for the test. Since the means and standard deviations of the populations are unknown, the t-test was chosen. As a result of the test and according to the *p*-value in Table 6a, it can be concluded that there is no statistical evidence to accept the null hypothesis, since the *p*-value is below α. Therefore, there was a change in the mean breaking force of the short side of the armature after the voltage change. However, based on the data shown in the mean values (mean in Table 6), the change generates a decrease in the breaking force, which contradicts the intended outcome. The *p*-value in Table 6b suggests that there was no change in the breaking force of the long side of the armature after the voltage change. However, a significant change in the data dispersion was observed, as shown by the values of the corresponding standard deviations (StDev in Table 6). To evaluate the effectiveness of this modification in consistently meeting the specification, the company in this case study employs the Ppk index. This index leverages extensive data collected over time to factor out external influences on the process. It relies on the standard deviation of the entire data set (σ = S) as an estimate for process variation, as shown in Equation (1). In this case, with only one lower specification limit and aiming for higher detachment force values, a higher Ppk indicates better process capability.

$$\text{Ppk} = \left[\frac{\mu - EI}{3\sigma_L}\right] \tag{1}$$

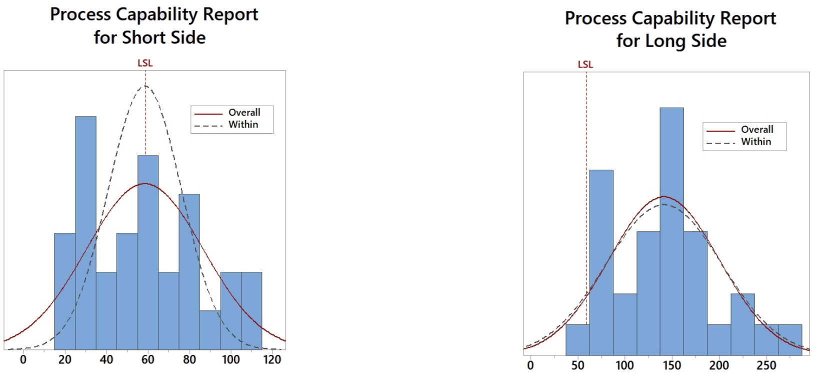
where:

μ = the average of the data obtained from the variable under study (the force necessary to detach the epoxy coating from the armature) in N;

EI = the detachment specification (in N);

σ_L = the long-run standard deviation (in N).

Compliance analysis based on Figure 19 and Table 7 clearly demonstrates that the implemented curing process modification fails to meet the specification. Both the short-side Ppk of 0 and the long-side Ppk of 0.47 fall significantly short of the company's minimum acceptable value of 1.32. However, it is important to consider the following crucial clarification: prior to these experiments, peel strength measurements (see Section Epoxy Coating Peel Test) were conducted incorrectly, potentially inflating the observed capacities. Therefore, while the current data show reduced capability compared to those earlier measurements (Table 5), they provide a more accurate picture of the process performance.



(**a**) (**b**)

Figure 19. Histograms of detachment force capability response to curing station voltage increase: (**a**) short-side armature; (**b**) long-side armature.

Table 7. Detachment force capability response to curing station voltage increase.

Process Data:				**Overall Capability**		
	Short-Side Armature		**Long-Side Armature**		**Short-Side Armature**	**Long-Side Armature**
LSL	58.8399		58.8399	PPL	0	0.47
Sample mean	58.5133		141.347	Ppk	0	0.47
Sample N	30		30	Potential (within) capability		
Overall StDev	28.0494		58.3937	CPL	−0.01	0.45
StDev (within)	17.6576		61.4867	Cpk	−0.01	0.45
Performance:						
	Observed		Expected Overall		Expected Within	
	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature
PPM < LSL	500,000	33,333.33	504,644.93	78,835.22	507,378.31	89,818.74
PPM total	500,000	33,333.33	504,644.93	78,835.22	507,378.31	89,818.74

Testing Different Thicknesses of the Epoxy Coating to Find the Optimal Balance between Insulation and Production Efficiency

To potentially address the low detachment force observed earlier, a second test increased the epoxy coating thickness. The thickness was raised from its original 0.250 mm to 0.350 mm while maintaining the previously tested curing voltage of 3.1 kV. Table 8 shows the results of a mean difference test for breaking force before and after changing the epoxy layer thickness.

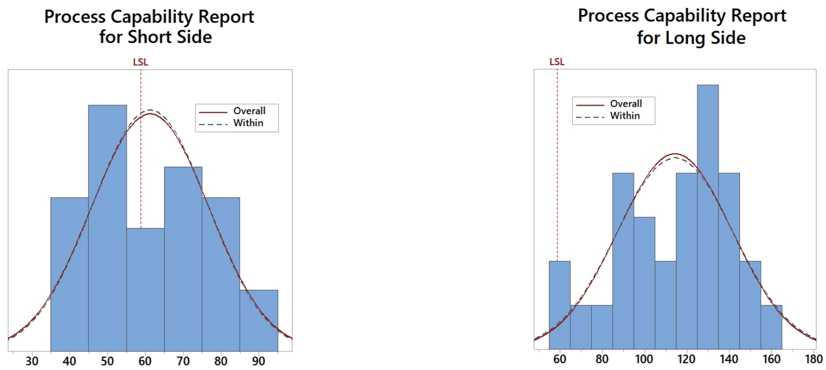
The aim is to statistically evaluate whether there was a change after this modification, taking the initial data obtained in the previous adjustment (the voltage change) as reference. The significance level and type of test were the same as those used to evaluate the previous change. As a result of the test and according to the *p*-value in Table 8a, it can be concluded that there is statistical evidence to accept the null hypothesis, since the *p*-value is not below α. Therefore, there was not a change in the mean breaking force of the short side of the armature after the epoxy coating adjustment. However, a slight increase was observed based on mean values (Table 8a). The *p*-value in Table 8b suggests that there was a change in the breaking force of the long side of the armature after adjustment of the epoxy coating. Increasing the epoxy thickness proved promising, resulting in boosted Ppk values on both sides; the short side increased from 0 to 0.05 (Table 9 and Figure 20), and the long side, from 0.47 to 0.69 (Table 9 and Figure 20). While encouraging, these values still fall short of the company's minimum acceptable Ppk of 1.32, indicating further optimizations are needed.

Table 8. Mean difference test results for breaking force before and after increasing the epoxy coating thickness: (a) short-side armature; (b) long-side armature.

	(a)					**(b)**			
	N	**Mean**	**StDev**	**SE Mean**		**N**	**Mean**	**StDev**	**SE Mean**
C3	30	58.5	28.0	5.1	C4	30	141.3	58.4	11
C5	30	61.3	15.5	2.8	C6	30	114.4	27.0	4.9
C3 = Data before 2nd experiment					C4 = Data before 2nd experiment				
C5 = Data after 2nd experiment					C6 = Data after 2nd experiment				
Difference = μ (C3)—μ (C5)					Difference = μ (C4)—μ (C6)				
Estimate for difference: −2.75					Estimate for difference: 26.9				
95% CI for difference: (−14.53, 9.04)					95% CI for difference: (3.2, 50.7)				
T-Test of difference = 0 (vs ≠)					T-Test of difference = 0 (vs ≠)				
T-Value = −0.47					T-Value = 2.29				
p-Value = 0.641 DF = 45					p-Value = 0.027 DF = 40				

Table 9. Detachment force capability response to epoxy coating thickness increase.

Process Data:				**Overall Capability**		
	Short-Side Armature		**Long-Side Armature**		**Short-Side Armature**	**Long-Side Armature**
LSL	58.8399		58.8399	PPL	0.05	0.69
Sample mean	61.2592		114.412	Ppk	0.05	0.69
Sample N	30		30	Potential (within) capability		
Overall StDev	15.5159		26.9718	CPL	0.05	0.67
StDev (within)	15.2593		27.5506	Cpk	0.05	0.67
Performance:						
	Observed		Expected Overall		Expected within	
	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature
PPM < LSL	500,000	33,333.33	43,8046.75	19,681.94	437,013.53	21,843.95
PPM total	500,000	33,333.33	43,8046.75	19,681.94	437,013.53	21,843.95

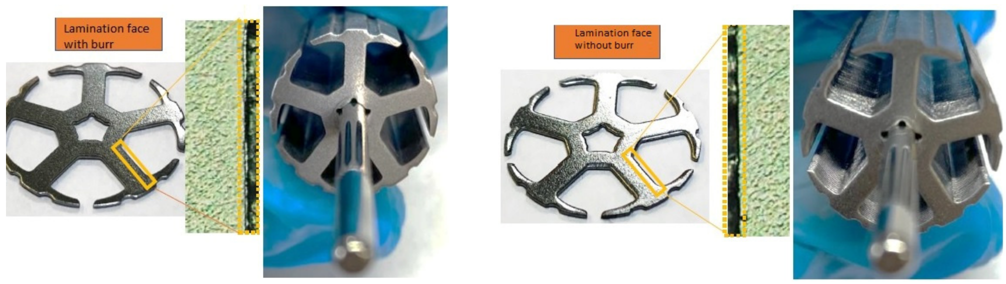


(**a**) (**b**)

Figure 20. Histograms of detachment force capability response to epoxy coating thickness increase: (**a**) short-side armature; (**b**) long-side armature.

Evaluating the Impact of Rotating the Lamination Faces 180° on the Compatibility of the Armature Body with the Epoxy Coating

Maintaining the voltage range (3.0–3.1 kV) and epoxy thickness (0.200–0.350 mm), a third experiment focused on the lamination rotation based on the observed higher break force on the long side. Rotating the laminations 180° consists of flipping all laminations to the other side throughout the entire length of the armature. Analysis revealed the lamination has two distinct sides: one flat and one with a raised edge (burr) where the detachment force is applied. Figure 21a shows a lamination side with a prominent burr, while Figure 21b depicts a burr-free side. These burrs caused insufficient insulation, allowing cable insertion to reach the lamination and creating an electrical path between the cable and the metal (continuity).



(**a**) (**b**)

Figure 21. Lamination face (**a**) with burr and (**b**) without burr.

This situation is particularly evident on the short side of the armature because the face with the burr is positioned towards the side where the commutator bar is located (Figure 22). The commutator has to be accurately associated by the stack slots whenever pushed on top of the shaft because the wires from every coil will appear from the slots, as well as attaching to the commutator bars. This is where the winding experiences a higher force, as it is where the coil turns are generated. This generates higher pressure, pushing the wire against the epoxy coating. The presence of a burr on this side of the laminations may further contribute to these stresses, potentially explaining the occurrence of hipot failures, and highlights the need for a solution to burr formation during lamination. Rotating all the laminations 180° proved to be a successful solution. This is because the long side of the armature lacks a collector, resulting in less tension on the cable winding compared to the short side. Figure 3 illustrates the perspective of the long side of the armature. It can be observed that the cable is only routed from one slot to another. Despite the presence of a burr due to the rotation of all the laminations, there is no tension to press the cable against the epoxy coating. This helps to prevent hipot failures. A t-test for mean differences was performed using the same parameters as the previous tests performed in this study. A sample of 27 armatures showed a significant change in the mean detachment force on the short side compared to the last change (epoxy layer thickness adjustment). This conclusion can be explained by the *p*-value shown in Table 10. This significant improvement suggests superior adhesion, potentially eliminating the previously encountered hipot failures.

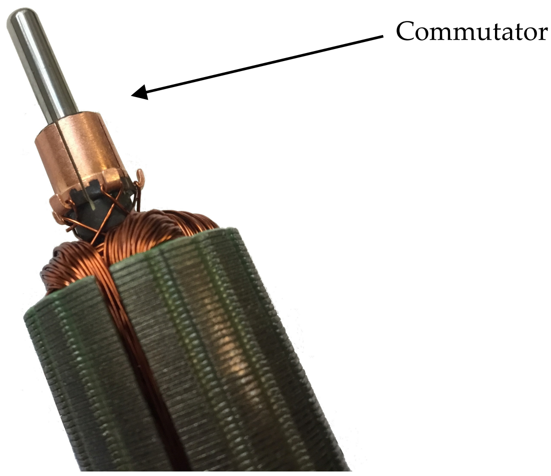


Figure 22. Detailed view of the commutator and its winding, together with the stack.

Table 10. Mean difference test results for breaking force before and after rotating the lamination faces 180°: (a) short-side armature; (b) long-side armature.

(a)					(b)				
	N	**Mean**	**StDev**	**SE Mean**		**N**	**Mean**	**StDev**	**SE Mean**
C5	30	61.3	15.5	2.8	C6	30	114.4	27.0	4.9
C7	27	291.4	73.3	14	C8	27	105.2	23.1	4.5
C5 = Data before 3rd experiment					C6 = Data before 3rd experiment				
C7 = Data after 3rd experiment					C8 = Data after 3rd experiment				
Difference = μ (C5)—μ (C7)					Difference = μ (C6)—μ (C8)				
Estimate for difference: −230.2					Estimate for difference: 9.23				
95% CI for difference: (−259.7, −200.7)					95% CI for difference: (−4.09, 22.54)				
T-Test of difference = 0 (vs ≠)					T-Test of difference = 0 (vs ≠)				
T-Value = −16.00					T-Value = 1.39				
p-Value = 0.000 DF = 28					*p*-Value = 0.170 DF = 54				

In addition to the positive outcomes observed on the short side, inverting the lamination also produced favorable results for the long side as well. The test conducted on the long side, as shown in Table 10b, revealed no statistical evidence to reject the hypothesis of equal means before and after inverting the faces of the laminations. This indicates that there was even a small change in the mean breaking force values on the long side. This can be explained because this improvement was mainly focused on improving the breaking force on the short side.

Inverted lamination proved to be highly beneficial, as evidenced by the marked improvement in terms of meeting specifications. Table 11 and Figure 23 illustrate a notable increase in the short side's Ppk, which surged from 0.05 to 1.06, bringing it closer to the minimum target of 1.32. Conversely, Table 11 and Figure 23 also indicate that the long side experienced negligible change. However, the overall result is that both sides now demonstrate significantly enhanced process capability.

Table 11. Detachment force capability response to epoxy coating thickness increase.

Process Data:			**Overall Capability**			
	Short-Side Armature		**Long-Side Armature**		**Short-Side Armature**	**Long-Side Armature**
LSL	58.8399		58.8399	PPL	1.06	0.67
Sample mean	291.441		105.186	Ppk	1.06	0.67
Sample N	27		27	Potential (within) capability		
Overall StDev	73.2918		23.1488	CPL	1.26	0.65
StDev (within)	61.6931		23.741	Cpk	1.26	0.65
Performance:						
	Observed		Expected Overall		Expected Within	
	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature	Short-Side Armature	Long-Side Armature
PPM < LSL	0	0	752.74	22,637.33	81.53	25,460.03
Total PPM	0	0	752.74	22,637.33	81.53	25,460.03

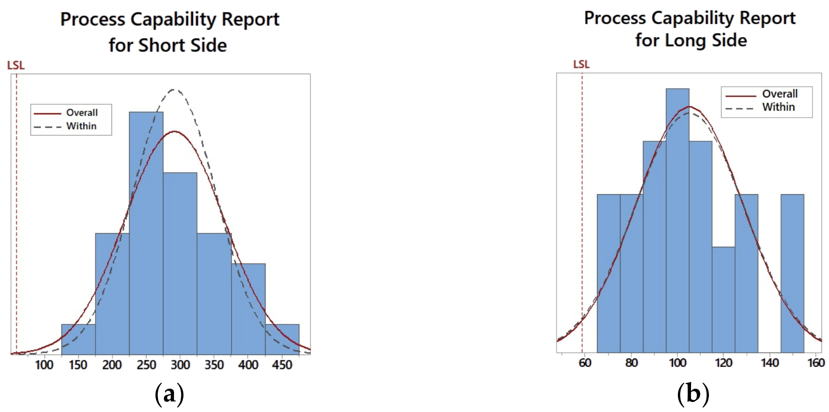


Figure 23. Histograms of detachment force capability response to inverting the lamination: (**a**) short-side armature; (**b**) long-side armature.

This achievement strongly indicates that inverted lamination could serve as a pivotal solution to address the detachment force issue previously identified in the manufacturing process.

Differential Scanning Calorimetry Test

To conclude these two phases of the PDCA cycle and ensure the epoxy's performance with the implemented modifications, a DSC study was conducted. This study aimed to investigate the behavior of the epoxy powder during changes in curing temperature. Specifically, the study focused on determining whether the epoxy degraded under these conditions, as this directly impacts the functionality, quality, and durability of the reinforced motor.

The DSC analysis compared a virgin epoxy sample to a cured sample, as depicted in Figures 24 and 25. The results revealed a curing percentage of 84.23%.

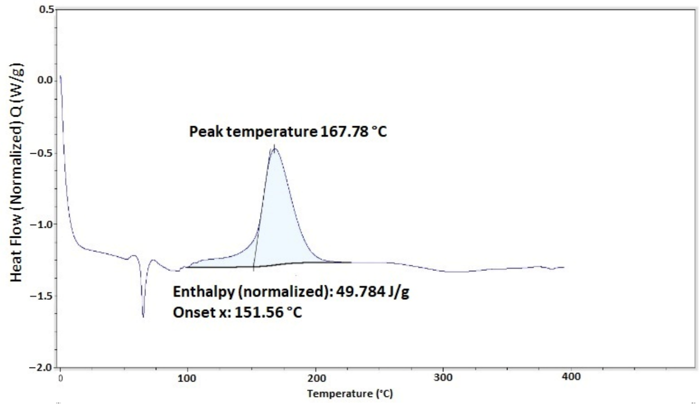


Figure 24. DSC test on a virgin sample (without curing treatment).

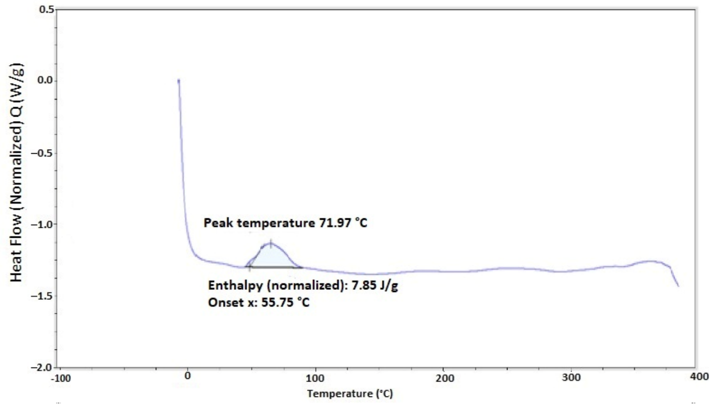


Figure 25. DSC test on a cured sample.

To ensure proper performance and adhesion, the percentage of epoxy curing needs to be precisely measured. This is calculated using the following equation:

$$\% \text{ Curing} = (1 - \Delta H)/\Delta H_0 \times 100 \quad (2)$$

Enthalpy represents the total energy content of a system at constant pressure. In the context of epoxy curing, ΔH_0 denotes the energy change when the uncured epoxy fully cures, while ΔH represents the energy change during partial curing stages. Comparing these values allows us to accurately assess the extent of epoxy curing throughout the process.

This information is crucial for ensuring the final product meets the desired quality and performance standards. Understanding the enthalpy changes helps in monitoring and controlling the curing process to achieve consistent and reliable epoxy properties.

To determine the optimal voltage setting to maximize the epoxy curing percentage, experiments were conducted, varying the curing process voltage from 2.8 to 3.3 kV. The epoxy layer thickness was maintained at 150–200 microns, while the degreasing voltage remained at 2.6 kV.

Analysis of data from both the short side (Figure 26) and long side (Figure 27) revealed that 2.9 kV achieved the highest curing percentage on both sides. This finding shed light on the potential reasons for the poor breaking force results observed when increasing the voltage in the curing process, as discussed in Section Adjusting the Voltage at the Epoxy Coating Curing Station to Optimize Curing Conditions.

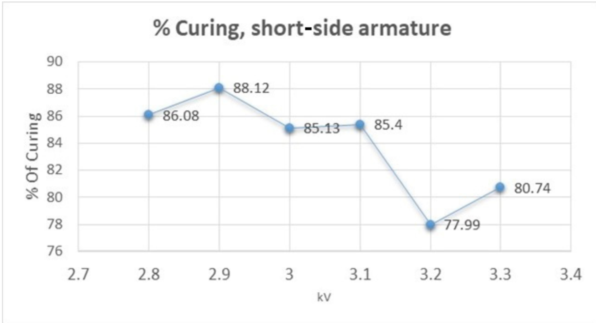


Figure 26. Curing percentage as a function of voltage, short-side armature.

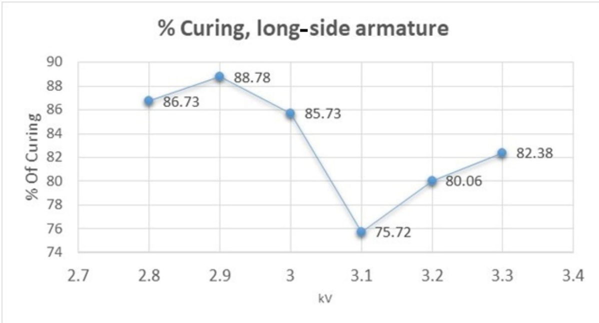


Figure 27. Curing percentage as a function of voltage, long-side armature.

4.1.3. Phase 4: Act

This phase aimed to solidify and enhance the previously implemented changes, ensuring long-term process efficiency. These adjustments were presented to management, highlighting their impact in terms of meeting specifications. No modifications were made to the physical equipment or tooling; instead, adjustments focused solely on operating parameters and new instructions for the turning process in lamination. To sustain these gains, they were documented in the control plan and the organization's PFMEA. The voltage increase tested in Section Adjusting the Voltage at the Epoxy Coating Curing Station to Optimize Curing Conditions was not implemented based on the findings of the DSC study.

5. Results

The graph in Figure 28 illustrates the behavior of the scrap indicator two months after implementing the improvements. The organization had set a 0.7% scrap target, which was significantly surpassed. This accomplishment can be attributed to the enhanced capability to meet the detachment force specification for the epoxy coating, thereby reducing hipot test failures in motors. Notably, the short side no longer yielded 500,000 pieces outside the specification, a key factor in surpassing the scrap target.

Figure 28. Scrap per month, January–October 2022.

These changes yielded substantial economic benefits. Taking into account the combined savings in metallic pieces, wire, and epoxy powder, the total annual cost reduction amounts to approximately USD 135,000.

6. Conclusions

This case study demonstrates the effectiveness of the PDCA methodology in reducing scrap within the electric motor manufacturing process. Implementation of the PDCA cycle significantly enhanced the production process, achieving the scrap reduction goal of 0.7% and exceeding it. This success was achieved through the identification and analysis of root causes associated with the hipot problem. The main areas identified included contact with the laminate during the epoxy coating application and sharp edges in the lamination process itself.

In addition to scrap reduction, this study highlights the critical role of continuous process improvement and the utilization of tools like 5W + 2H and three-legged five-why analysis in pinpointing and addressing defect root causes. The implementation of these tools enabled a targeted and effective approach to problem-solving, ultimately resulting in reduced scrap.

This study differentiates itself from previous work by integrating statistical tools (control charts and capability analysis), quality tools (5W + 2H and three-legged five-why analysis), and the PDCA cycle into a unique framework. This framework addresses a specific need in the armature manufacturing process by tailoring the 'Do' and 'Check' phases to include specialized testing procedures for identifying hipot issues. This customized framework guides scrap reduction for processes prone to hipot failures while simultaneously enhancing quality and reducing costs. This approach ultimately elevates the efficiency of operations management within this sector. The specific details of the case study serve as a practical example of how the PDCA cycle can be implemented to address hipot issues in electric motor subassembly lines. Educational institutions can utilize this case study to illustrate a real-world application of continuous improvement methodologies within a dynamic industry. In addition, the automotive industry, particularly the electric vehicle segment in China, is experiencing rapid growth. The presented case study offers valuable insights into a critical aspect of electric motor production (scrap reduction) relevant to this expanding market. By showcasing a successful implementation, this case study can serve as a starting point for other manufacturers in the region or globally facing similar challenges.

6.1. Implications for Theory

The current state of knowledge of PDCA also explores the following aspects:

(a) Integration with other quality management frameworks: This research achieves this goal by combining PDCA with other quality tools like capability analysis and control charts for a more comprehensive approach to continuous improvement. In addition, this research proposes a simplified version of the PDCA cycle, combining the "Do" and "Check" phases into a single "Do/Check" phase. This streamlined approach can expedite the achievement of results.

(b) Application in specific contexts: While this study was applied in electric motor manufacturing, the framework's replicability allows for adaptation and application in organizations that manufacture products with wire windings. This includes generators, alternators, pumps, transformers, switchgears, and similar equipment.

6.2. Implications for Practice

A key practical contribution of the methodology proposed in this study is that it serves as a basis for meeting the specific requirement of clause 10.2.3 of the IATF 16949 standard. The documented steps of the methodology provide a process for problem-solving and preventing recurrence in similar situations of high-potential (hipot) defect generation.

6.3. Limitations and Future Research

One limitation of this manuscript is that the experimentation was conducted considering only one size of armature. This was because the hipot issue was specifically occurring in that type and size of armature. It is likely that a broader approach could uncover additional solutions beyond those found in this study, which may not have been detected due to size constraints.

Based on the results obtained in this case study, it is advisable to continue seeking improvements in the capability to meet the specification for the detachment force of the epoxy coating. While the set goal in this study was accomplished with some margin, it remains essential to aim for the desirable value of 1.32 for the Ppk, as mandated by the company. For future research, it is recommended to employ a factorial experimental design, considering various levels of the factors examined in this investigation. This approach will enable a more comprehensive analysis of the effects of the factors and their interactions on the response variable.

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