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IMPROVING IMMO COIL QUALITY VIA SIX SIGMA

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Abstract: This paper takes the Immobilizer antenna (referred to as IMMO) in J Company's keyless entry and start system (Passive Entry and Passive Start, PEPS) as the research object. Using the Six Sigma method, a systematic analysis and improvement were conducted to address the issue of high C/1000 (defects per thousand units) of this component. Through the five stages of Define, Measure, Analyze, Improve, and Control, the key process variables affecting product quality were identified and optimized. The research results show that by improving the winding fixture, optimizing the heating temperature control, and introducing insulation detection between turns, the C/1000 of the IMMO antenna was significantly reduced, thereby improving product quality and customer satisfaction. The research in this paper provides useful references for the quality management of similar products in the automotive electronics industry.
Keywords: Six Sigma; Quality improvement; IMMO; Short circuit detection

1 INTRODUCTION

Quality management assumes a crucial and central position within the manufacturing sector. It functions as the linchpin for ensuring that products adhere to anticipated standards, fulfill customer demands, and fortify the competitiveness of enterprises [1].

PEPS (Passive Entry and Passive Start) system is gradually becoming a main stream option in automotive keyless entry application, which improves the convenience and vehicle anti-theft performance[2]. With the automotive industry experiencing exponential growth, the quality and reliability of automotive electronic products have become subjects of heightened scrutiny[3]. During every phase of automotive component production, spanning from the procurement of raw materials to the final delivery, meticulous supervision and control are not merely advisable but essential to consistently supply products that meet or exceed customer expectations.

Automotive component manufacturers, as suppliers, do not solely concentrate on the quality of the end product. Instead, they also place significant emphasis on identifying and rectifying process defects. For Supplier Quality Engineers (SQEs) working for automotive Original Equipment Manufacturers (OEMs), it is of utmost importance to systematically tackle process quality concerns by implementing the Six Sigma quality improvement methodology. This methodology consists of five sequential and iterative phases: Define, Measure, Analyze, Improve, and Control (DMAIC) [4]. By adopting this approach, it becomes possible to continuously optimize the production processes within the supply chain, thereby minimizing the costs associated with poor quality.

With the extensive application of the Passive Entry Passive Start (PEPS) keyless entry system, automotive key entry has advanced into the intelligent era [5]. The communication between the PEPS controller and the Immobilizer (IMMO) coil is a collaborative procedure that integrates short-range low-frequency wake-up and high-frequency encrypted verification.

The primary scenarios encompass production binding during the vehicle's off-line process, daily vehicle startup by the end-user, and emergency startup situations. The central aim is to allow users to operate the vehicle without the need to physically retrieve the key. Simultaneously, through the encryption mechanism, it effectively deters vehicle theft, thus enhancing the user experience and emerging as a crucial indicator of the competitiveness of contemporary vehicles.

2 PROJECT DESCRIPTION

This article meticulously analyzes the scenario of production halts resulting from IMMO coil failure. Prior to vehicle disassembly, a crucial process is the anti-theft binding of the key to the entire vehicle, known as "key learning"[6]. The system primarily encompasses the PEPS controller (PEPS integration), the IMMO coil along with its wiring harness, the key, and the transponder.

The principal steps are as follows: The assembly plant issues the "key learning" command to the PEPS controller via the diagnostic instrument. Subsequently, the PEPS controller activates the IMMO coil, enabling it to emit a low-frequency signal, typically at 125kHz, of a specific frequency. This signal contains both a wake-up instruction and the vehicle's unique ID. When the pre-bound smart key, which has a built-in transponder, enters the magnetic field of the IMMO coil, the transponder detects the low-frequency signal through its coil and activates the internal circuit. The transponder then transmits its unique ID (the key) to the PEPS controller via high-frequency (433MHz) and receives a response. The PEPS controller verifies the match between the key ID and the vehicle ID. If there are no discrepancies, it binds the two (the relevant information is stored in the encryption chip of the PEPS controller), thereby completing the "anti-theft authentication initialization".

When the vehicle is delivered to the client, in the event that the key has insufficient power, it can be placed in close proximity to the IMMO coil. Through mutual inductive charging between the key and the coil, low-frequency authentication can be achieved. Once the authentication is successful, the vehicle can be started in an emergency.

Nevertheless, Company J discovered during its actual production process that the C/1000 value of the IMMO coil was relatively high. This led to recurrent issues of failed key learning during vehicle disassembly, significantly undermining production efficiency and customer satisfaction. Consequently, undertaking a project to reduce the C/1000 value of the IMMO coil holds substantial practical significance.

3 IMPLEMENTATION OF SIX SIGMA

To the successful execution of the Six Sigma project greatly contributed the belief and support of top-management and the active involvement of team members [7]. As a systematic problem-solving tool, the core concept of Six Sigma is to be data-driven, using structured processes and statistical analysis methods to identify and eliminate negative factors affecting target indicators, thereby achieving operational performance improvement. In practical application, DMAIC (Define - Measure - Analyze - Improve - Control) is the most common and widely used implementation framework, applicable to quality improvement projects in various fields such as manufacturing and services. This paper takes the IMMO coil C/1000 reduction project as a case to explore its standardized implementation process, aiming to provide a reference operational model for quality improvement in the automotive parts industry.

3.1 Project Objectives and Implementation Plan

In May 2023, the SUV production line experienced a failure where vehicles could not be associated with car keys. The fault code was "B102049 09 immo coil failure". After swapping the ABA components, the fault was traced to the IMMO coil. Based on the analysis of fault data, the monthly C/1000 (number of faults per 1,000 units) reached 1.94. The team decided to reduce the C/1000 of the IMMO coil incoming material from 1.94 to 0.1, extending the challenging target to 0.05. The team formulated the project plan following the Six Sigma DMAIC (Define-Measure-Analyze-Improve-Control) methodology, as shown in Table 1.

Table 1 Project Schedule (Gantt Chart)

Project Tasks		D: 2023-07-20						M: 2023-08-22					A: 2023-09-27				I:2023-10-31				C: 2023-11-29				
		June				July				August				September				October				November			
Phase	Tasks	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W
D	Problem statement																								
	Process flowchart																								
	Determine the CTQs																								
	Define the goals																								
	Project Approval																								
M	Defining measurement methods																								
	Determine the data type																								
	Data collection plan																								
	Conduct MSA																								
	Assessment of process capability																								
A	Review Analysis Methods																								
	Select an analysis tool																								
	Apply graphic analysis tools																								
	Identify changes																								
I	Choose the improvement plan																								
	Conduct failure mode analysis																								
	Conduct a cost-benefit analysis																								
	Small-scale trial production																								
	Verify improvement																								
C	Develop control strategy																								
	Prepare the control plan																								
	Update the operation procedures																								

3.2 Define (Definition Phase): Define the Problem and the Objective

During the key-offline learning process at the assembly plant, the IMMO coil communicates with the key using a 125kHz low-frequency signal. In case of occasional failures, the learning process fails due to inability to resonate, and the vehicle cannot learn the key. The failure rate is 1.94 C/1000, and the performance is deteriorating. See Figure 1 for the trend chart of the problem. The IMMO coil's drawing specifies the inductance value specification as 162 ± 2% µH @ 125kHz. The measured value of the faulty part is 19.20 µH, indicating a low inductance. This coil is from a certain manufacturer. Therefore, the research scope of the project is the supplier's production process.

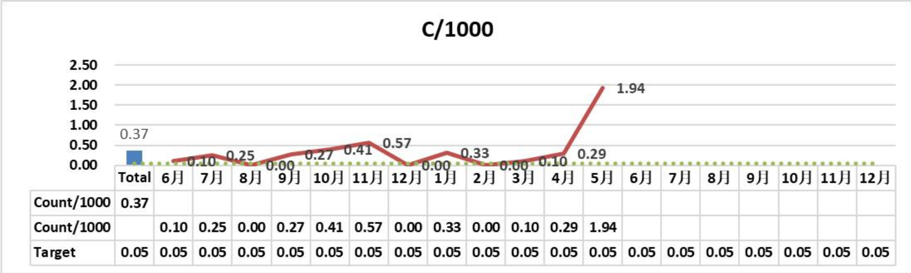


Figure 1 Trend Chart of the Problem

At the supplier's site, using the LCR measuring instrument (1V, 125kHz), the problem points were identified one by one: the insulation layer was damaged in the two outermost turns of the coil from the edge of the housing. The location of the injury is shown in Figure 2.

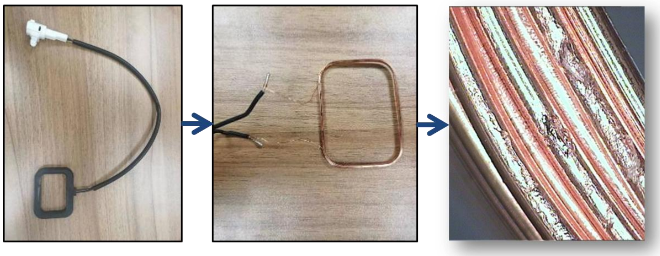


Figure 2 Location of the Injury

3.3 Measurement Phase: Quantification of Current Process Status

The core task of the measurement stage is to establish a measurement system for the suspected factors, collect data, and evaluate process capability.

Firstly, review the existing process flow, such as "incoming material inspection → winding → assembly and foot welding → injection molding → low-pressure injection molding → final product inspection", and identify the key processes with high impact. Use the SIPOC tool to analyze the influencing factors of each key process of the coil. The fishbone diagram aids in organizing complex information and offers a structured approach to decision-making and actual planning of maintenance interventions[8]. Figure 3 is Using the fishbone diagram to brainstorm and list the factors with high impact.

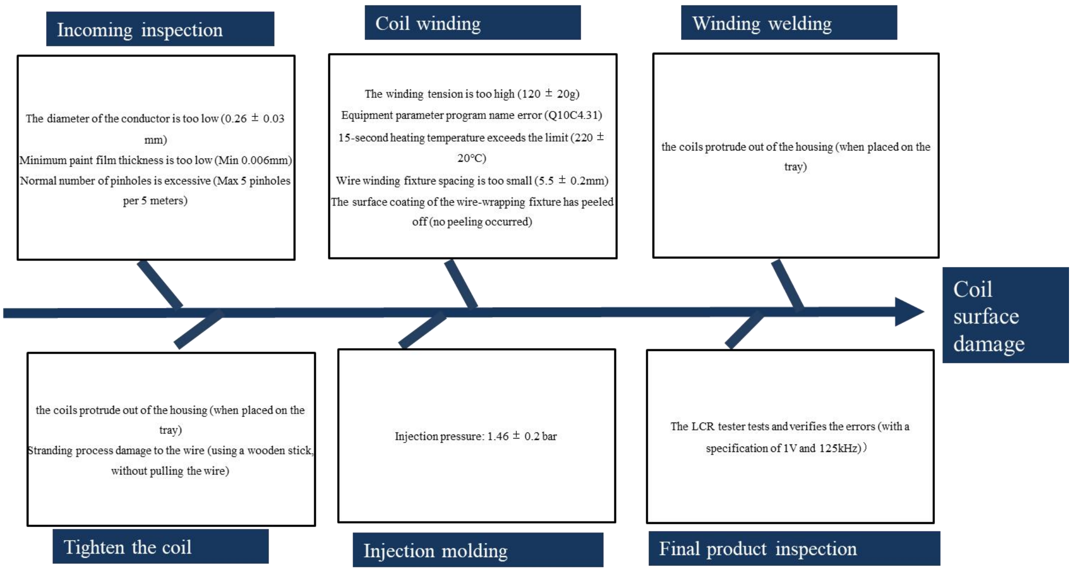


Figure 3 Fishbone Diagram

Then, the causal matrix table is used to evaluate the weight of each input variable on the defect. By analyzing the influence degree of each input parameter on the coil surface, seven key factors are determined: 1. Excessive winding tension, equipment program error, line damage, fixture coating off, low film thickness, too many pinholes, and LCR tester test error. Combined with the results of on-site production evidence investigation, as shown in Table 2, the remaining three impact factors after screening have insufficient evidence, and the three impact factors are in poor state, all of which need further study on process capability performance.

Table 2 Identify Key Factors

No	process	factor	evidence	stat
1	Incoming inspection	The diameter of the conductor is too low (0.26 ± 0.03 mm)	Incoming Material Inspection Report	A
2		Minimum paint film thickness is too low (Min 0.006mm)	Incoming Material Inspection Report	A
3		Normal number of pinholes is excessive (Max 5 pinholes per 5 m	Incoming Material Inspection Report	A
4	Coil winding	The winding tension is too high (120 ± 20g)	Initial inspection of the production line, unsure of the fluctuations during the production process	B
5		Equipment parameter program name error (Q10C4.31)	Daily inspection record form, OK.	A
6		15-second heating temperature exceeds the limit (220 ± 20℃)	Initial inspection before starting production - unsure about the fluctuations during the production process	B
7		Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Not actually measured	B
8		The surface coating of the wire-wrapping fixture has peeled off (r	The surface of the fixture is worn, but the extent of the damage is uncertain.	C
9	Tighten the coil	the coils protrude out of the housing (when placed on the tray)	Forming material tray, after transfer, there is no risk of material spilling out of the shell.	A
10		Stranding process damage to the wire (using a wooden stick, with	After inspecting the materials, conduct a magnifying glass examination to ensure there are no damages.	A
11	Injection molding	Injection pressure: 1.46 ± 0.2 bar	Real-time equipment monitoring shows no abnormalities in the production inspection record sheet.	A
12	Final product inspection	The LCR tester tests and verifies the errors (with a specification c	There is an NTF item, and the re-mounting function is not qualified.	C

Process Elements	
Element OK	A
Investigating	B
Element Not Capable	C
Element Removed	D

Before the process capability analysis, it is necessary to ensure the reliability of the measurement system, that is, to formulate sampling plans for key processes (winding, inspection), and analyze the measurement system. The summary results are shown in Table 3.

Table 3 Measurement System Analysis Results

No.	Key Factor	Item	Data Type	Sample size	Frequency	Tool	Result	Date
1	X1:The winding tension is too high (120 ± 20g)	winding tension	Variable data	30	2 times/day	Tension meter	Gage R&R< 10%; NDC>5， acceptable	2023.8
2	X2:15-second heating temperature exceeds the limit (220 ± 20°C)	heating temperature	Variable data	10	2 times/day	Temperature meter	Gage R&R< 10%; NDC>5， acceptable	2023.8
3	X3:Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Wire winding fixture spacing	Variable data	10	2 times/day	Vernier caliper	Gage R&R< 10%; NDC>5， acceptable	2023.8
4	X4:The surface coating of the wire-wrapping fixture has peeled off	fixture has peeled off	Attribute data	10	2 times/day	Visual inspection	Kappa value > 0.8, acceptable	2023.8
5	X5:LCR tests and verifies the errors (with a specification of 1V and 125kHz))	LCR tester test error	Attribute data	300	Continuous	High-voltage tester	Kappa value < 0.8, unacceptable	2023.8

Among them, in the LCR tester process, 30 measurement objects were prepared (20 coils with varying degrees of damage and 10 good coils), and two operators conducted repeated measurements twice, with a total of 120 tests. The misjudgment rate of the equipment for faulty parts was 47% (NG judged as OK), and the Kappa value was less than 0.8, making the measurement system unacceptable, as shown in Figure 4. The primary measure for fault analysis is to protect the customer, and it is urgent to implement a new detection method for the current situation. After benchmarking with the same industry, an additional high-voltage test was added, using a 2900V high-voltage tester (based on 70% of the 4200V insulation voltage of the enameled wire) to detect energy loss. The MSA verification Kappa value was greater than 0.8, which was acceptable.

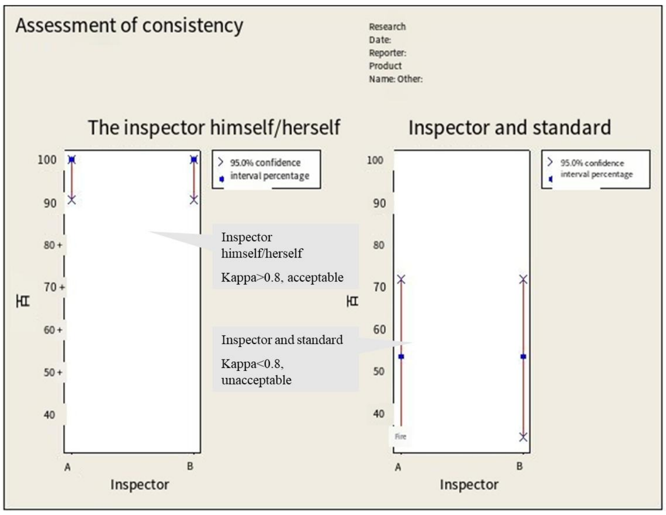


Figure 4 Assessment of Consistency

Based on a qualified measurement system, process capability analysis was conducted. According to the target of CPK >

1.33 and DPMO less than 3.4, it was found through investigation and analysis that the surface coating of the winding fixture was peeling off， as table 4 shows.

Table 4 Process Capability Analysis Results

No.	Key Factor	Item	Data Type	Sample size	Frequency	Tool	data presentation	Result
1	X1:The winding tension is too high (120 ± 20g)	winding tension	Variable data	30	2 times/day	Tension meter	CPK=2.23	acceptable
2	X2:15-second heating temperature exceeds the limit (220 ± 20℃)	heating temperature	Variable data	10	2 times/day	Temperature meter	CPK=1.35	acceptable
3	X3:Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Wire winding fixture spacing	Variable data	10	2 times/day	Vernier caliper	CPK=1.44	acceptable
4	X4:The surface coating of the wire-wrapping fixture has peeled off	fixture has peeled off	Attribute data	10	2 times/day	Visual inspection	The surface Teflon coating has peeled off, exposing the base material / twice	unacceptable
5	X5:LCR tests and verifies the errors (with a specification of 1V and 125kHz))	LCR tester test error	Attribute data	300	Continuous	High-voltage tester	DPMO=20000	unacceptabl

3.4 Analyze (Analysis Stage): Identify the Root Cause

After checking the surface coating of the winding fixture, it can be clearly seen that there is wear at the contact position of the coil. The outermost anti-wear layer of the fixture has been scratched. And touch by hand, can obviously feel the position of the contact coil is rough and not smooth. The high voltage tester (2900V) was used to continue to check the bare coil. The coil produced by the fixture was 3170 PCS, and the faulty parts with insufficient voltage tolerance were 6 PCS. Observe its air discharge position, which is located in the left and right section of the coil in Figure 5 below, which is exactly the contact surface between the coil and the fixture.

Further process confirmation is carried out to confirm that the surface coating of the winding fixture has not been regularly inspected since it was put into use in 2021, there is no relevant maintenance requirements, and there is no life management.

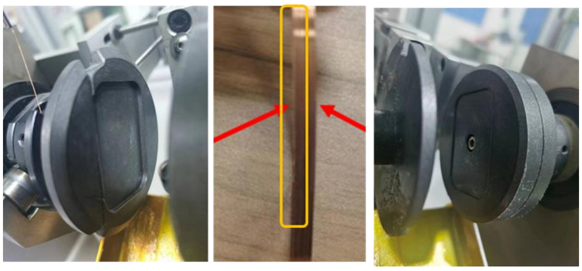


Figure 5 The Coil Damage Point and the Fixture Position Correspond

3.5 Improve: Implement the Optimization Plan

Regarding the problem of the wire clamping fixture falling off, a new fixture was immediately customized. The produced coils with the new fixture were analyzed for data. The reliability of the fixture was verified by analyzing the change in the defect rate. This fixture was identified as a spare part for the winding machine equipment. A maintenance plan was formulated, and a replacement frequency was determined. The coating condition of the production coils was confirmed daily at the start of each shift. Additional spare parts were added, and the production clamps were required to be replaced compulsorily every 6 months and re-coated at the factory. Other devices in contact with the enameled wire, such as the lead-out pins, felt pads, and idler pulleys, were expanded laterally to increase protection and maintenance.

Although the team has been using high-voltage testers as recommended by the industry to supplement the measurement of inter-turn micro-short circuits in the coils, for the winding density of this coil, it is still worth the team to continue to increase the sample size for research on how much test voltage to use. The research method is as follows: Take 20 faulty pieces and conduct 50 tests each at 500V, 1000V, 2000V, and 2500V. The experimental results are shown in Table 5. The experiment indicates that a 100% result repeatability can be achieved at 2500V. Based on industry experience, the detection voltage is set at 70% of the conductor's rated voltage. The IMMO coil enameled wire withstands a voltage of 4200V. The final test voltage is set at 2900V and updated in the PFMEA and control plan.

Table 5 High-voltage Test Results under Different Measurement Voltages

Voltage（V）	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
500	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1000	10%	4%	4%	2%	4%	0%	0%	2%	6%	4%	0%	0%	8%	6%	0%	2%	4%	6%	2%	2%
2000	100%	92%	82%	76%	78%	88%	86%	92%	100%	92%	86%	84%	86%	82%	72%	76%	78%	82%	100%	100%
2500	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

By adding clamping accessories and re-coating the surface, a high-pressure energy loss test was conducted on the coils before and after the repair of the original coating of the clamping fixtures. The inventory pieces produced by the fixtures with the original coating that had fallen off were re-examined, and 11,018 pieces were re-examined, with 20 NG (non-conforming) items detected. After replacing with new coated fixtures, 6,000 pieces were produced, and 1 NG item was detected.
Based on the above test data, using the two-ratio hypothesis test, it was confirmed whether the defect rate of the coils produced after the fixture coating repair decreased.
▪ Sample 1: Coils before fixture coating repair
▪ Sample 2: Coils produced after using the new fixture
▪ H0: P1 = P2, the test defect rate before and after fixture replacement is consistent
▪ Two-ratio test: As shown in Figure 6, P < 0.05, Reject H0, there is a difference between the two states.
▪ The current sample size is sufficient to meet the efficacy requirements.
Conclusion: After replacing the fixtures, there is a significant improvement.

Two-ratio test and confidence interval
sample X N sample p
1 20 11018 0.001815
2 1 6000 0.000167

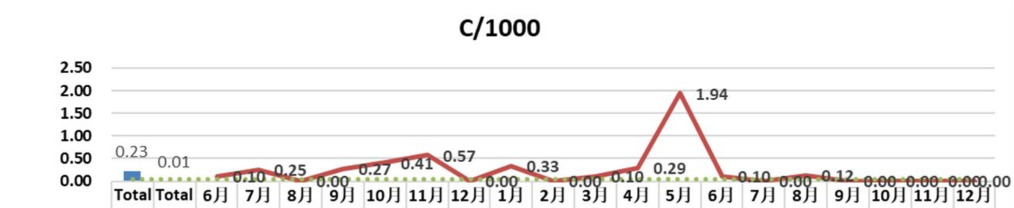
P<0.05, Reject the null hypothesis

Gap = p (1) - p (2)
Gap estimation : 0.00164854
The 95% confidence interval for the gap: (0.000789231, 0.00250786)
Test for the gap being equal to 0 (versus not equal to 0): Z = 3.76 P-value = 0.000
Fisher's exact test: P-value = 0.002
Note * The normal approximation for small samples may not be accurate.

Figure 6 Two-ratio Hypothesis Test

With the newly produced modified components, the failure rate during loading has dropped to nearly 0, showing a significant improvement. The trend of failure data is shown in Table 6.

Table 6 Trend of C/1000



	Total	Total	6月	7月	8月	9月	10月	11月	12月	1月	2月	3月	4月	5月	6月	7月	8月	9月	10月	11月	12月
Count/1000	0.23	0.01																			
Count/1000			0.10	0.25	0.00	0.27	0.41	0.57	0.00	0.33	0.00	0.10	0.29	1.94	0.10	0.00	0.12	0.00	0.00	0.00	0.00
Target	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

3.6 Control (Control Phase): Solidify the Improvement Achievements

Based on the core achievement of significantly reducing the IMMO coil C/1000 by this project, great emphasis was placed on the long-term implementation and experience accumulation of improvement measures. Through systematic document upgrades and the establishment of platform-based preventive mechanisms, the sustainable implementation of quality improvement results was ensured.
At the level of document system updates, all key documents of the entire process have been revised and verified:
▪ PFMEA (Process Potential Failure Mode and Effects Analysis) has added failure mode analyses such as "inter-turn short circuit of the coil" and "coating detachment of the fixture causing insulation damage", supplemented with potential risk points such as failure of high-voltage tests and abnormal stray capacitance, clearly specifying preventive control measures for factors such as fluctuation in winding tension and unstable heating temperature, reducing the RPN (Risk Priority Number) from the high-risk range before improvement to below the industry benchmark value, and forming a risk early warning model covering the entire chain of design, production, and inspection.

▪ The control plan (CP) has focused on strengthening the monitoring requirements for key process parameters, such as increasing the inspection frequency of the coating status of the winding fixture from "monthly" to "mandatory inspection at the start of each shift", adding 2900V voltage calibration records for the high-voltage tester (once per shift), clearly defining the dual-criterion standards for inductance value and energy loss rate (inductance 162 ± 2% μH@125kHz and energy loss ≤ 5%), and uploading test data to the MES system for real-time traceability to achieve a closed-loop.
▪ Standard operation procedures (SOP) have refined operational norms, including the debugging steps of the winding machine tensioner, safety precautions during high-voltage tests, and the first-piece verification process after fixture replacement, with accompanying graphic and textual operation diagrams to ensure that front-line employees can directly refer to and execute, reducing human operational deviations.
▪ In terms of experience accumulation and platform-based prevention, the project team has incorporated the "fault mode - root cause - control measure" experience library formed by this improvement into the enterprise sharing platform:
▪ Through enterprise knowledge base updates, subsequent new projects can call upon the risk data in this FMEA during the design stage, avoiding similar issues such as inter-turn short circuit and failure of detection methods in advance, achieving the preventive effect of "one improvement, multiple benefits".
After cross-departmental joint review and confirmation, these documents have been released and come into effect. The consistency of on-site execution is 100%, and the process capability monitoring for 3 consecutive months shows that the IMMO coil C/1000 is stably controlled below 0.05, verifying the effectiveness of the solidification measures, and accumulating replicable practical experience for the standardization and platformization of enterprise quality improvement.

4 CONCLUSION

The IMMO coil C/1000 reduction project, using the DMAIC methodology as the framework, through precise problem definition, scientific process measurement, in-depth root cause analysis, efficient implementation of improvements, and strict control implementation, not only did IMMO coil C/1000 achieve a breakthrough improvement from 1.94 to below 0.05, but also established a replicable quality improvement system. The upgrade of the entire process documents from PFMEA, control plans to SOPs transformed scattered improvement experiences into standardized management norms; while the platform-based accumulation of the "failure mode - prevention measures" experience database broke the boundaries of a single project and provided forward-looking preventive ideas for the quality control of similar products and even across different fields. The closed-loop implementation of the project not only verified the practical value of Six Sigma in manufacturing quality improvement, but also demonstrated the profound significance of the "data-driven, systematic policy, and continuous accumulation" quality concept in enhancing enterprise competitiveness, laying a solid foundation for subsequent high-quality development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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