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Improvement of Automated Dual-liquid Potting Process Using Flow Sensors

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To improve product quality and ensure process stability, high standards are required for automated dual-liquid potting, aiming to quantitatively evaluate its process capability and enhance quality control and consistency during mass production. In this study, we focus on improving the potting and encapsulation process for electronic products. The process involves mixing a base agent (epoxy resin) with a curing agent (amine resin) in a specific ratio. The mixture is injected into products containing electronic components and circuitry using automated equipment or manual operation. After curing at room temperature or with heating, an insulating protective layer is formed, providing adhesion and sealing functions. During this process, unfavorable environmental conditions or component malfunctions may lead to process failures, resulting in a high defect rate, increased production costs, and negative impact on overall output. The goal of this study is to enhance equipment stability and implement preventive strategies to ensure optimal operating conditions. After the system was implemented, the number of defective products was successfully reduced to within 10%, achieving stable production quality. A programmable logic controller was used in conjunction with communication protocols such as RS-485, Ethernet/IP, and MODBUS to collect key process parameters such as pressure, temperature, and flow rate, which directly affect product quality and allow the real-time monitoring of both product and equipment status. Furthermore, three-way ANOVA was used to simulate different operational scenarios (normal, upper limit, lower limit, and abnormal conditions) to evaluate the impact of each factor on process stability, mixing quality, and product reliability. Through data analysis, standard procedures were developed for routine maintenance, preventive servicing, and the prediction of remaining equipment life, with the aim of improving production efficiency and reducing defect rate.

1. Introduction

As electronic products evolve toward higher performance, miniaturization, and multi-functionality, operational environments and reliability requirements become increasingly

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stringent. To ensure the stable functioning of internal electronic components and prolong product lifespan, sealing and protection processes have become indispensable in manufacturing. The potting process is widely applied in electronic component packaging owing to its excellent insulation, moisture resistance, and mechanical protection properties.(1) Potting processes commonly use dual-liquid materials such as epoxy resin and polyurethane. The materials are mixed in a specified ratio and injected into the interior of products via automated systems or manual means, then cured at room temperature or with heat to form an insulation protective layer. Critical process parameters such as pressure, flow rate, and temperature significantly affect final product quality. Imbalances in mixing ratio, abnormalities in injection volume, or equipment aging can lead to defective products or complete failure, increasing production costs and reducing throughput. Enhancing equipment stability and establishing effective monitoring have become urgent challenges in the industry. In this study, we integrate programmable logic controllers (PLCs) and industrial communication protocols (e.g., RS-485, MODBUS, and Ethernet/IP) with flow, pressure, and temperature sensors to collect key process data. These are combined with real-time monitoring and data analysis techniques to construct a smart potting system with early warning capabilities to reduce failure rate and enhance process reliability.

1.1 Literature review

Potting is a key electronic packaging technique used to encapsulate components with protective materials for insulation, waterproofing, dustproofing, vibration resistance, and extended service life.(2) It is widely applied in automotive electronics, power modules, sensors, and other high-reliability applications. Tire pressure monitoring system (TPMS) safety modules heavily depend on potting quality to ensure system stability and performance.(3) Common potting materials include epoxy, polyurethane, and silicone. Epoxy resins are known for their mechanical strength and electrical insulation, making them ideal for fixing sensitive electronic components. Polyurethane offers elasticity and weather resistance, making it suitable for vibration or outdoor environments.(4) With the rapid advancement of automotive electronics, TPMS has become a standard safety feature, drawing increasing research attention.(5) As an essential sensing unit in automotive safety systems, TPMS monitors tire pressure in real time and issues alerts to mitigate driving risks. The potting stage of TPMS transmitters significantly affects their waterproofing, vibration resistance, and electromagnetic compatibility performance.(6) In standard processes, dual-liquid potting systems dynamically mix base and curing agents in ratios ranging from 4:1 to 5:1. If the mixture ratio is inaccurate or dispensing is unstable, and the system lacks proportional monitoring, deviations may go undetected. The effects result in incomplete chemical reactions, insufficient curing, poor mechanical strength, and insulation failure. The defects undermine process stability and product reliability.(7) To ensure consistency, modern potting lines incorporate real-time sensors for flow, pressure, and temperature, feeding data back to PLC controllers. Visualization and logging are achieved through human–machine interfaces (HMIs).(2) To further enhance process control, manufacturers increasingly implement automated inspection technologies such as automated optical inspection, widely used for verifying printed circuit board (PCB) solder quality, component alignment, and assembly accuracy. The systems eliminate human error, improving early yield and product quality. The continuous monitoring of adhesive flow, pressure, and temperature ensures accurate mixing ratios and stable delivery, effectively preventing defects such as bubbles and poor mixture uniformity caused by heat fluctuations or flow instability.[8] Advanced potting platforms now integrate flow, pressure, and temperature sensors with PLC and HMI systems to establish real-time monitoring environments with dynamic compensation and fault warning mechanisms. The platforms can build process databases to support future optimization and predictive maintenance. The technology aligns with the core of smart manufacturing.[9,10]

Smart manufacturing is defined as a manufacturing trend that provides a flexible and adaptable production process, helping to overcome the challenges faced by production facilities in an increasingly complex environment.[11] In the manufacturing process, the production procedure not only needs to be able to cope with high flexibility and small-batch production but also requires the integration of system information.[12] Smart Factory as a decentralized production system can be realized in real time among work pieces, machinery, processes, personnel, and resources.[13] Various data analysis and machine learning techniques were utilized in the manufacturing process to illustrate the importance of data-driven for enhancing process capability.[14] Establishing a smart system that integrates various technologies is beneficial for providing better supply chain resilience, particularly in procurement, manufacturing, and inventory management.[15] The future factory is expected to possess attributes such as complex manufacturing equipment structures, diverse functions, multiple sensor types, high sampling frequency, complex operating conditions, and heterogeneous business information systems.[16] The smart factory does not imply a peopleless factory; human–machine collaboration is also a developmental trend during the transition period of the smart factory,[17] gradually adjusting, changing, and optimizing existing production models, thereby influencing the role of humans in the factory's production process. On the digital basis, lean management can achieve real-time production monitoring and process optimization through the use of digital tools and reduce production waste through continuous improvement to improve resource utilization efficiency.[18]

1.2 Methodology

The dual-liquid potting system employed in this study uses epoxy resin as the primary encapsulating material. The base agent (epoxy) and curing agent (amine compound) are mixed at a predetermined ratio and dispensed into module cavities via automated potting systems to form sealed structures. If the mixing ratio is inaccurate or the process control is poor, issues such as bubble formation or incomplete curing may arise, compromising product reliability and longevity. The potting process imports smart manufacturing concepts increasingly. Various sensors (e.g., for temperature, pressure, and flow rate) are integrated for real-time monitoring. The sensors are connected with PLCs and standardized communication protocols (e.g., RS-485, Ethernet/IP, and Modbus) to enable remote control, real-time anomaly alerts, and predictive maintenance.

2. Experimental Method and Equipment

2.1 Automated dual-liquid potting process

The dual-liquid potting process is widely applied in the protective encapsulation of electronic modules and critical components. The process ensures insulation, moisture resistance, and vibration resistance by precisely mixing the resin and hardener and using automated dispensing systems. The process flow can be divided into four main stages as follows.

(1) Raw material preparation

The potting materials consist of a base resin (e.g., epoxy) and a curing agent (e.g., amine compound), which are stored separately in designated containers, as shown in Fig. 1. The materials are delivered to the mixing system via pressurized pneumatic or electric systems.

(2) Material delivery and ratio control

For proper curing and product quality, it is important to control the ratio accurately. Materials prepared in the raw material stage are delivered via pressure systems into metering pumps. Ratio control is executed on the basis of preset mixing ratios (e.g., base:hardener = 4:1 to 5:1) using fixed gear ratios, where flow rates are governed by gear module and speed. However, traditional systems often lack real-time sensing feedback. The pump wear, viscosity changes, and unstable pressure rely entirely on manual inspections or scheduled maintenance. The issues are difficult to detect in real time and can damage potting consistency or cause product defects.

(3) Mixing and potting operation

After precise ratio control, the resin and hardener are delivered to a dynamic mixing valve for homogeneous blending. The mixing valve may use static mixers with helical blades or motor-driven rotary shafts to generate rotation and shear. The process can ensure uniform mixing and avoid stratification or incomplete reactions (Fig. 2).

(4) Curing and downstream processes

After dispensing, the resin must be cured to achieve insulation and environmental sealing. Typical equipment includes thermal ovens, hot air chambers, or heated molds. Curing time and temperature vary depending on the resin type; for example, epoxy resin may require

Fig. 1. (Color online) Base resin (epoxy) and a curing agent (amine compound).

Fig. 2. (Color online) Mixed resin pipeline.

heating at 60 °C for over 2 h to complete crosslinking and form a stable 3D network. Table 1 and Fig. 3 illustrate the curing parameters used in this study.

Precise temperature control and environmental stability are keys to curing quality. A uniform temperature distribution should be maintained using thermal humidity-controlled environments.

It is necessary to apply moisture-sensitive resins to the dehumidification system to avoid bubble formation, haziness, or curing failure. After curing, the product proceeds to cooling, inspection, functional testing, and packaging. Visual inspection checks for defects such as bubbles, delamination, or overflow. Traditionally, these steps rely on manual inspection with no real-time feedback or digital traceability. With smart manufacturing advancements, modern workflows incorporate traceability systems and the digital management of process data. By integrating sensors with PLCs, data such as temperature, curing time, and environment are continuously collected and stored locally or on the cloud. Combined with HMI display and manufacturing execution system (MES) integration, the capabilities enable real-time alerts, production history tracking, and quality analysis for improved process stability and efficiency.

2.2 Intelligent potting system architecture

To improve the stability and intelligence of automated dual-liquid potting processes for high-reliability applications, in this study, we propose an integrated intelligent potting system. The

Table 1
Curing data after potting.

Time (**min**)	Temperature (**°C**)	Illustration
0	25	Initial temperature
5	35	Increase temperature slowly to prevent internal expansion
10	50	Continuous heating
15	60	Reach setting curing temperature
15~135	60 (Continuous)	Curing phase at constant temperature
135~150	45~30	Decrease temperature slowly
>150	25	Return to room temperature to complete curing

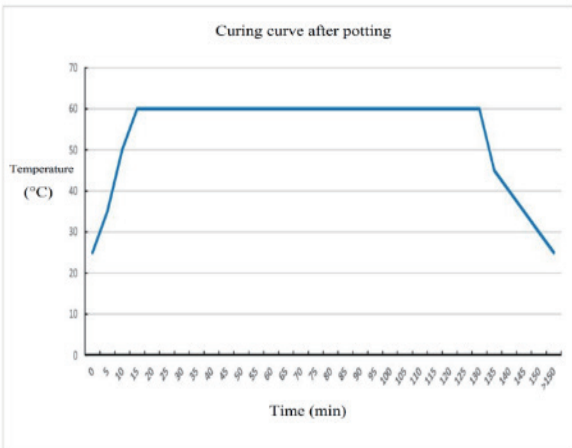

Fig. 3. (Color online) Curing curve after potting.

system includes four functional modules: sensor monitoring, PLC control, HMI display, and historical data analysis. The system allows for real-time access to key process parameters and enables fault prediction and predictive maintenance. Pressure, temperature, and flow rate sensors are installed at the air intake of the resin tank, within the tank body, and upstream of the mixing valve. Selected sensors include piezoresistive pressure sensors, high-precision flow meters, and self-adhesive K-type thermocouples. The sensors are designed for stable long-term operation in high-viscosity and corrosive environments. By continuously monitoring the parameters, the system ensures accurate ratio mixing and stable material delivery and prevents defects. The analog signals collected by the sensors are converted to digital signals and sent to the PLC. A Mitsubishi FX5U series PLC is used, featuring multi-point input, high-speed processing, and modular expansion, making it ideal for the real-time control of multiple sensors. The PLC interprets sensor data and compares it with preset thresholds, triggering corresponding actions such as valve shutoff, pausing operation, or activating alarms. The system reduces reliance on human intervention and increases response speed. The HMI serves as the communication bridge between operators and equipment. It displays real-time sensor data, alerts, parameter settings, and operation logs. With graphical and hierarchical interface design, operators can efficiently assess system status and adjust parameters. The HMI also supports historical data queries for traceability and quality improvement.

Finally, the system includes a historical data module that records PLC-sampled sensor data to a local or cloud database. When abnormal parameter deviations are detected, the PLC logic can trigger alarms in real time, prevent process failures, and guide predictive maintenance strategies.

2.3 Intelligent potting system architecture

In the design of the intelligent potting system, proper sensor selection and layout planning are key to achieving process stability, product consistency, and intelligent monitoring. In this study, we incorporated three sensors (flow, pressure, and temperature) into an automated dual-liquid potting system. These are integrated with the PLC control structure based on their application requirements and communication protocols. For flow monitoring, the FD-XA1 clamp-on noncontact flow sensor is selected. It provides high accuracy and minimal interference, suitable for detecting variations in the flow rates of dual-liquid potting materials. Its advantage is the noncontact measurement, which eliminates contamination or residue concerns, while simplifying maintenance and cleaning routines.

For pressure control, a resistive pressure sensor (NP43P-010-F1) is installed at the inlet side of both the base and hardener tanks. The model delivers stable output with high sensitivity and linearity, providing 1–5 V analog signals for input to the PLC A/D converter module for real-time monitoring and curve visualization. Regarding temperature control, the system uses self-adhesive K-type thermocouple sensors mounted on the tanks and along the delivery tubing to monitor temperature fluctuations during material transport. The sensors offer linear response, high accuracy, and corrosion resistance, making them suitable for extended operation under high humidity, heat, and reactive conditions. The FY400 controller receives output from the thermocouples and regulates heating elements or coils on the basis of the preset thermal profile.

It supports preheating, temperature maintenance, and overheat warning functionalities. With built-in over-temperature protection and alarm outputs, it helps prevent premature reactions or bubble formation due to overheating, while archived data serves as a basis for process optimization. All sensors are modularly connected to the PLC and networked via communication protocols including EtherNet/IP, RS-485, and analog voltage. This architecture enables the comprehensive visualization, digitization, and smart management of the potting process, ensuring product quality and process reliability.

2.4 PLC and HMI control modules

To achieve the precise control and real-time monitoring of the automated dual-liquid potting process, in this study, we applied a Mitsubishi PLC as the core control unit, in combination with an HMI module for user interaction and data display. The PLC integrates signals from various sensors (flow, pressure, and temperature) and executes control commands such as valve operation, preheating activation, and potting start/stop sequences according to logic flow. The PLC program divides the potting process into raw material supply, dynamic mixing, potting control, data monitoring, and troubleshooting. For example, the NP43P-010-F1 pressure sensor delivers a 1–5 V analog signal to the PLC input module. K-type thermocouples and the FY400 controller connect via RS-485 half duplex communication. The FD-XA1 clamp-on flow rate sensor cooperates the NU-EP1 Ethernet module and the GW-7473 gateway for EtherNet/IP and Modbus conversion.

The HMI is designed with multi-layered display operational workflows, providing real-time parameter visualization, historical data tracking, alarm displays, and manual test modes (as shown in Figs. 4 and 5). Users can view ratio settings, initiate potting processes, or acknowledge alerts directly from the HMI, improving usability and interaction efficiency. When the system detects anomalies such as sudden flow rate drops, abnormal pressure, or overheating, it triggers alerts on the HMI with both visual and auditory signals while automatically executing protection logic such as shutting output valves. Furthermore, the system includes data logging and analytics capabilities. Real-time data collected by the PLC is stored per second in an internal database, visualized via the HMI, and provides maintenance planning and control optimization. The PLC Ethernet port also allows future integration with supervisory control and data acquisition (SCADA) systems or industrial cloud platforms for remote monitoring and smart manufacturing implementation.

2.5 System integration and process flow

2.5.1 System integration mechanism

To achieve the intelligent monitoring and real-time management of the automated dual-liquid potting process, in this study, we integrated multiple sensors, a PLC, an HMI, and communication protocols (Modbus and Ethernet/IP) to construct an intelligent potting system with capabilities including data acquisition, process monitoring, data analytics, and predictive maintenance.[6] The architecture and functionality are shown as follows.

Fig. 4. (Color online) Real-time parameter visualization.

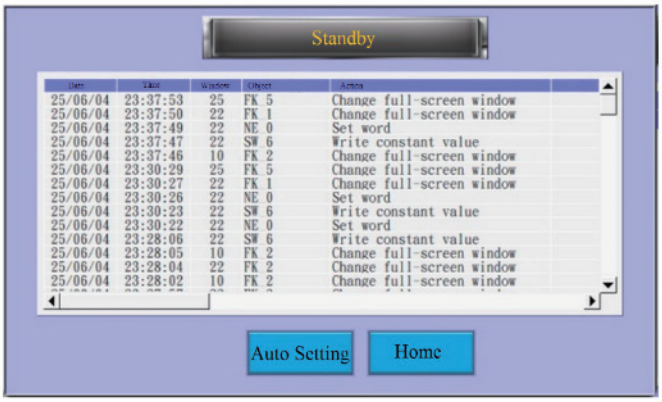

Fig. 5. (Color online) Historical data tracking.

(1) Sensor layer: Includes flow rate, pressure, and temperature sensors responsible for the real-time data acquisition of process parameters.
(2) Signal processing unit: Converts raw sensor data into standardized formats.
(3) PLC: Executes data reception, logic computation, and process control commands.
(4) Communication module: Transfers data via Modbus RTU/TCP or Ethernet/IP for integration with HMI or higher-level supervisory systems.
(5) HMI/SCADA system: Provides interfaces for on-site and remote monitoring and operation.
(6) Data storage and analysis module: Archives historical data for optimization and traceability analysis.
(7) Predictive maintenance and anomaly alert system: Issues maintenance suggestions or anomaly notifications on the basis of the results of trend analysis, enhancing system stability.

This integration improves effectively the automation, intelligence, and reliability of the potting process. The division of functionalities and data flow among subsystems is illustrated in the system integration flowchart (Fig. 6).

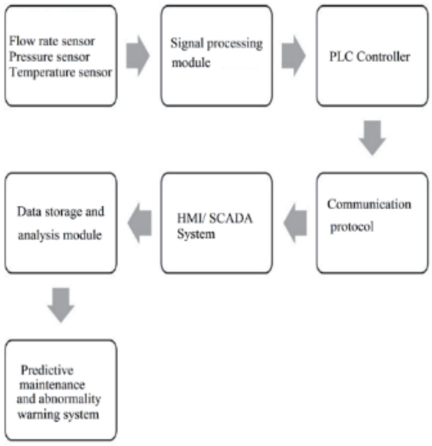

Fig. 6. System integration flowchart.

2.5.2 System installation

In this study, the intelligent dual-liquid potting system has been built up completely in the laboratory to verify the effectiveness of the system integration. All key components including sensors, a PLC control module, HMI, and communication modules were installed on the potting equipment according to process requirements, with the communication setup and data acquisition validated. The installation considers industrial spatial constraints and layout feasibility to ensure maintainability and signal integrity. Details of the actual setup are as follows.

(1) Sensor installation diagraphs: As shown in Figs. 7 and 8, the flow sensor is mounted on the base resin pipeline. The pressure sensor is installed at the top lid of the storage tank (Fig. 9), whereas the temperature sensor is located near the resin storage tank, with feedback displayed on the monitor (Fig. 10) to keep track of the real-time temperature of the potting material. The sensor configuration can ensure the timely and accurate measurement of key process parameters.
(2) PLC control box layout diagram: The actual layout includes the Mitsubishi PLC main unit, I/O modules, sensors, control relays, and power modules, as shown in Fig. 11.
(3) HMI: Screenshots of the HMI display, including real-time graphs and alert windows. Operators can confirm potting parameters through this interface (Fig. 12).
(4) Full equipment setup: Overall system structure showing spatial arrangement and layout from raw material tanks, delivery pumps, and mixing lines to sensors and control boxes (Figs. 13 and 14).
(5) Communication network diagram: Communication architecture between Modbus RTU or Ethernet/IP modules and upper level computers or SCADA systems, illustrating the data transmission workflow (Fig. 15).

Fig. 7. (Color online) Base resin pipeline.

Fig. 8. (Color online) Curing agent pipeline.

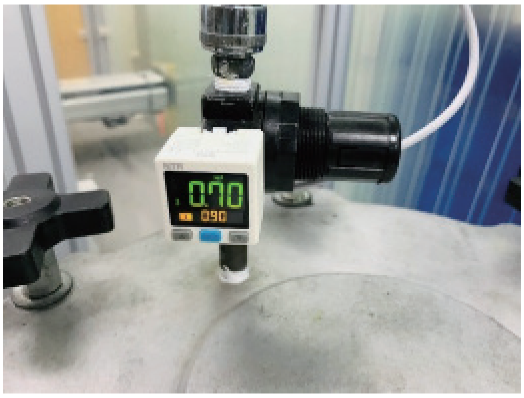

Fig. 9. (Color online) Pressure sensor.

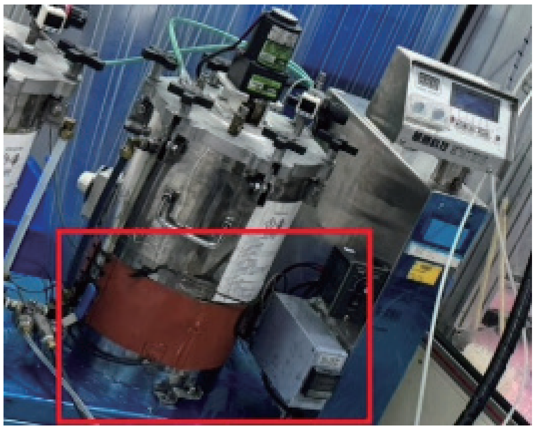

Fig. 10. (Color online) Temperature sensor.

2.5.3 Automated potting decision flow

According to the automated dual-liquid potting system logic flowchart (Fig. 16), the standard operational flow is depicted as follows.

During the initial detection phase, the PLC data acquisition module is activated to continuously acquire sensor data, including temperature, pressure, and flow rate. If all readings fall within the normal range, the potting process begins. Throughout the production cycle, the monitoring system continuously analyzes sensor data to ensure that parameters remain within specified limits until the cycle is completed. If any sensor reports an anomaly during the detection or production phase, the system immediately halts operation and initiates the troubleshooting protocol. Upon the completion of the production cycle, the system terminates

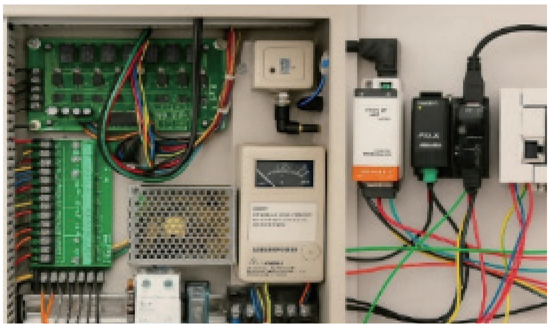

Fig. 11. (Color online) Architecture of PLC control box.

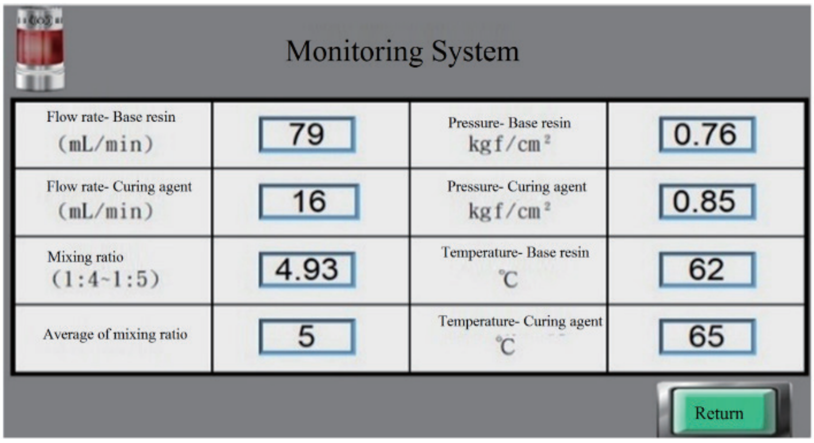

Fig. 12. (Color online) HMI.

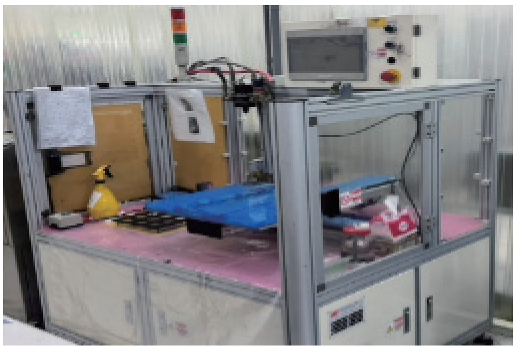

Fig. 13. (Color online) Platform of automatic potting equipment.

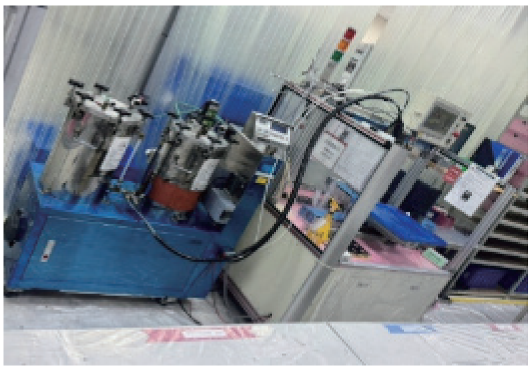

Fig. 14. (Color online) Full equipment setup of automatic potting.

monitoring. If any parameter such as temperature, pressure, or flow exceeds its limit during operation, the process is instantly stopped and rectification is initiated. After anomalies are solved, the system re-enters the monitoring phase. Once all sensor values return to normal, the production resumes until the cycle is successfully completed.

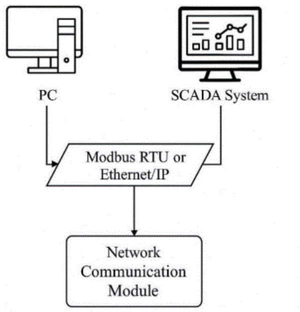

Fig. 15. System communication architecture.

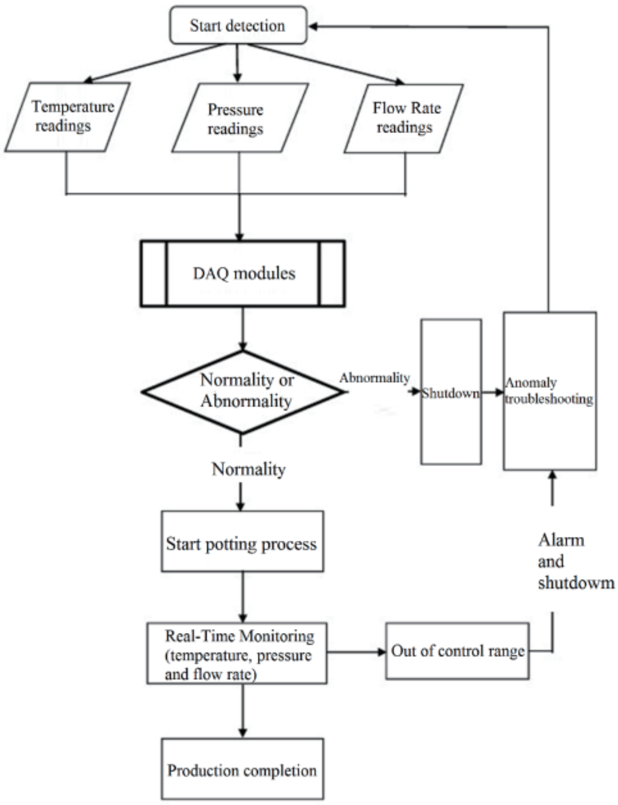

Fig. 16. Automated dual-liquid potting system logic flowchart.

3. Experimental Results and Discussion

3.1 Experimental framework

In this study, we aim to optimize process parameters and evaluate quality stability in automated dual-liquid potting operations. The monitoring system was established by integrating flow, pressure, and temperature sensors to evaluate how various potting conditions affect product quality.

The effects of key parameter variations on process stability and defect rates can be validated on the basis of the experimental design. Ultimately, the improvement strategies are proposed to enhance encapsulation quality for high-reliability automotive electronic products.

The experimental framework includes the following steps:
(1) establish a monitoring system equipped with flowmeters, pressure sensors, and temperature sensors,
(2) investigate the effects of different potting conditions (flow ratio, pressure, and material temperature) on the process,
(3) conduct actual production testing and collect key data, and
(4) analyze correlations between potting quality and anomaly.

3.2 Design of potting parameter experiments

Three-way ANOVA was employed to investigate the effects of flow rate, pressure, and material temperature during potting. The primary equipment was an automated dual-liquid potting machine. Table 2 shows the experimental ranges for each parameter.
(1) Flow rate: 70 to 90 mL/min
(2) Dispensing pressure: 0.5 to 0.9 kgf/cm^2
(3) Material temperature: 55 to 75 °C

3.3 Impact of parameter variations on quality

Dual-liquid potting materials are highly sensitive to mixing ratios. If the deviations between resin and hardener exceed ±11%, issues such as incomplete curing or bubble formation may arise, which can impact reliability severely and cause internal sensor module failures. To assess the impacts of temperature, flow rate, and pressure on mixing quality, four experimental conditions were set up as follows.
(1) Standard condition: Parameters set at mid-range baseline: temperature of 65 °C, flow rate of 80 mL/min, and pressure of 0.7 kgf/cm^2, simulating a stable production environment
(2) Lower limit condition: Parameters minimized: temperature of 55 °C, flow rate of 70 mL/min, and pressure of 0.5 kgf/cm^2 to observe the effects of these parameters on mixing uniformity and curing
(3) Upper limit condition: Parameters maximized: temperature of 75 °C, flow rate of 90 mL/min, and pressure of 0.9 kgf/cm^2 to simulate high loading conditions and assess their effects on reaction rate and bubble formation

Table 2
Ranges of each variable.

Parameter	Level		
	Low	Medium	High
Flow rate (mL/min)	70	80	90
Dispensing pressure (kgf/cm^2)	0.5	0.7	0.9
Material temperature (°C)	55	65	75

(4) Abnormal condition: Parameters set to extreme values: temperature of 25 °C, flow rate of 50 mL/min, and pressure of 0.3 kgf/cm^2 to simulate process failure due to equipment anomalies

3.4 Anomaly analysis

Figure 17 illustrates the anomaly analysis of production samples, detailing the equipment models used, the actual time of abnormal events, and whether the equipment was in auto-potting mode at the time. The feature analysis of anomaly samples was conducted using a fishbone diagram (Fig. 18), identifying three major causes: temperature, flow rate, and pressure. Through historical data comparison and analysis using the data-log system, trends and correlated parameters of anomalies were clearly traced, serving as a basis for future process improvements. Common anomalies, which include temperature deviation, insufficient flow rate, and abnormal pressure, are found in real production using the dual-liquid potting machine. The primary cause of these issues is the absence of real-time monitoring and feedback mechanisms, which delays detection by operators, adversely affecting product quality and process stability. The key sensors (temperature, flow rate, and pressure) were applied and integrated with a PLC system for data acquisition and analysis to address the issues. Paired with an HMI, the system offers real-time monitoring and anomaly alerts. This intelligent monitoring architecture improves process transparency and responsiveness, effectively mitigating undetected anomalies and enhancing the stability and reliability of the entire potting operation.

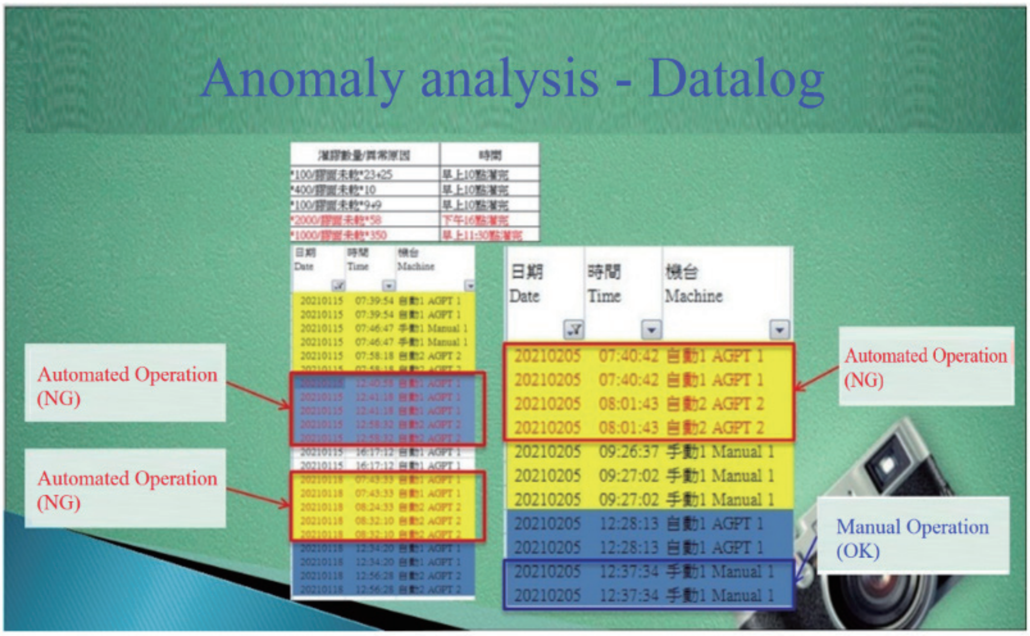

Fig. 17. (Color online) Anomaly analysis of production samples.

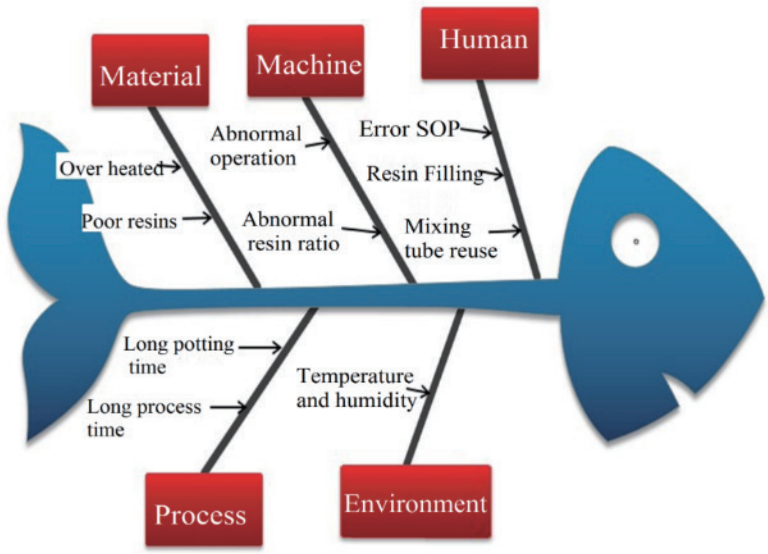

Fig. 18. (Color online) Cause and effect diagram (fishbone diagram).

3.5 System stability and deviation analysis

To verify the reliability of the sensor's output stability, calibration experiments and repeated encapsulation tests were conducted before the product was potted. The test results show that controlling each parameter within the set range ensures good stability and consistency during potting. The results of experiments conducted under normal operating conditions for the three factors are summarized in Table 3.

Abnormal Operating Conditions: The experiments were conducted under abnormal and extreme conditions with the following parameters: temperature at 25 °C, flow rate at 50 mL/min, and pressure at 0.3 kgf/cm^2. The conditions were used to simulate process failure due to equipment malfunction, as shown in Table 4.

The settings of each sensor parameter and their normal curves with upper and lower limits are as follows.
(1) Flow rate setting: 80 mL/min (standard value ± 12.5%), as shown in Fig. 19
(2) Pressure setting: 0.7 kgf/cm^2 (standard value ± 28.57%), as shown in Fig. 20
(3) Temperature setting: 65 °C (standard value ± 15.3%), as shown in Fig. 21

3.6 Results of system implementation

We successfully implemented a smart monitoring system for a dual-liquid potting process. By integrating flow rate, pressure, and temperature sensor modules with PLC control and an HMI, an automated monitoring platform was created for real-time monitoring and anomaly prewarning. Through the immediate feedback of sensor data and logical anomaly detection, the system can instantly trigger alerts to prevent sustained process losses caused by a malfunction.

Table 3
(Color online) Results of three-factor operation range.

Automated Dual-Liquid System	Normal	Lower Limits	Upper Limits
Potting Process	65°C 80 mL/min 0.7 kgf/cm²	55°C 70 mL/min 0.5 kgf/cm²	75°C 90 mL/min 0.9 kgf/cm²
Hardening	Good	Good	Good
Potting Sample			

Table 4
(Color online) Results of three-factor abnormal experiment.

Abnormal Experiment			
Extreme Condition	Failure Process	Hardening	Analysis
25°C 50 mL/min 0.3 kgf/cm²	Room temperature, pressure and flow rates below allowable values	Surface Softening	Parameters deviate from baseline and cannot be hardened
Potting Sample			

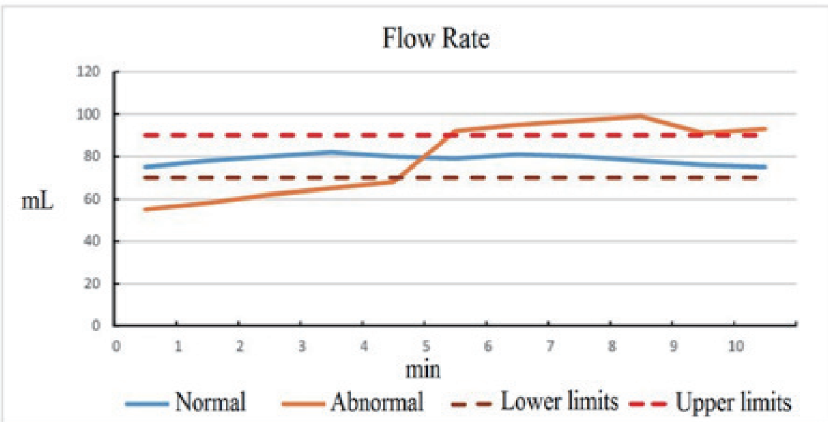

Fig. 19. (Color online) Flow rate range curve.

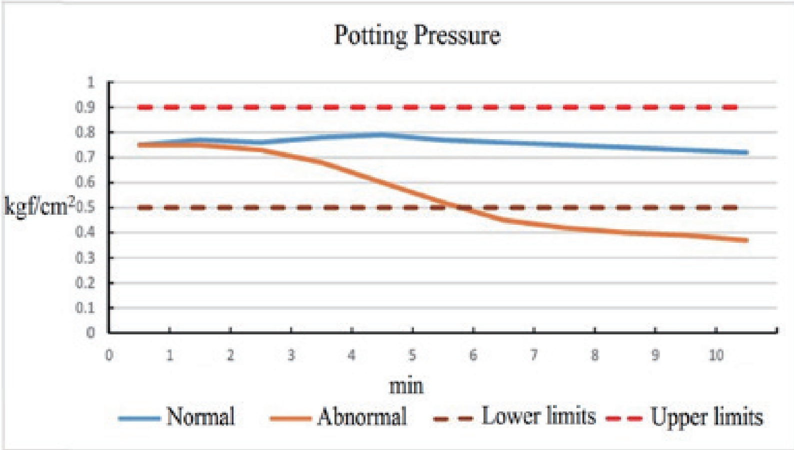

Fig. 20. (Color online) Potting pressure range curve.

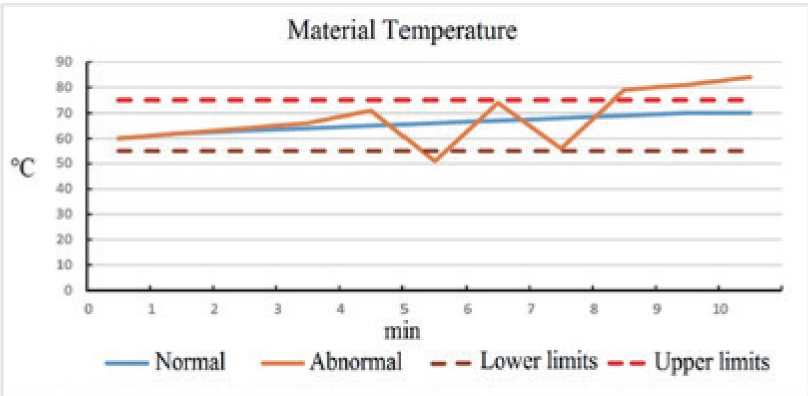

Fig. 21. (Color online) Material temperature range curve.

On the basis of scrap cost data (with an annual production of approximately 600000 units), the yearly scrap cost was as high as NT247752 in 2020, before the monitoring system was implemented. After the system was gradually introduced, the cost dropped to NT186442 in 2021. In 2022, with full system implementation, the cost was further reduced by half to NT93221. By 2024, the cost had fallen to just NT5593, demonstrating a significant improvement in process stability and the effectiveness of the prewarning mechanism. With the scrap cost as a key performance indicator, the improvement in cost and percentage compared with the 2020 baseline is as shown in Table 5.

3.7 Results of practical application

Operators can use the HMI to monitor the real-time process status and respond quickly to anomaly alerts, significantly improving the speed and accuracy of on-site operations. Managers can also use historical data for trend analysis and prewarning settings, allowing for early

Table 5
Scrap cost and estimated scrap quantity.

Year	Annual scrap cost (NT)	Improvement (compared with 2020)
2020	247752	Base Year
2021	186442	Approximately 24.7% decrease (early stage of improvement)
2022	93221	Approximately 62.4% decrease
2023	93221	Maintain improvement
2024	5593	Approximately 97.7% decrease

intervention in potential anomaly situations and preventing large-scale scrap and losses. After implementing the system, process stability was not only effectively improved, but the number of scrapped parts and associated costs were also drastically reduced, achieving a process management model that prevents defects at the source. The system demonstrates that it is possible to achieve smart manufacturing by integrating sensors and software technology without altering the existing equipment hardware.

In this study, we successfully built a smart potting monitoring system and practically implemented it on a packaging production line. With the estimated scrap cost as the metric, the cost was reduced from NT247752 (approximately 826 units) in 2020 to NT5593 (approximately 19 units) in 2024, representing a cost improvement of 97.7%. This system has not only enhanced process quality and stability but also significantly lowered operational loss costs. It proves that smart monitoring technology can be effectively applied to precision potting processes and can be expanded to other sensor modules or electronic packaging-related processes in the future.

4. Conclusions and Future Works

4.1 Conclusions

Epoxy resin monomers cannot cure on their own. The epoxy resin must form a three-dimensional network structure through a chemical reaction. To prevent premature hardening during storage due to premixing, adjustments to mixing ratios and properties should be facilitated. Curing speed, operating time, and post-curing properties (such as hardness and flexibility) can be adjusted as needed. If the mixture ratio is inaccurate, the effects result in incomplete chemical reactions, insufficient curing, poor mechanical strength, and insulation failure. The monitoring of adhesive flow, pressure, and temperature ensures accurate mixing ratios and stable delivery, effectively preventing defects such as bubbles and poor mixture uniformity caused by heat fluctuations or flow instability.

In this study, we presented an intelligent enhancement of the automated dual-liquid potting process by integrating three key process parameters, namely, flow rate, pressure, and material temperature, into a real-time monitoring system built as a PLC-based control platform. Through data acquisition and abnormality alert mechanisms, coupled with an HMI, the proposed system improves both operational efficiency and information transparency. A three-factor variation method was employed to simulate various scenarios, namely, normal, upper bound, lower bound, and abnormal, to assess their impacts on process stability, mixing quality, and product reliability. Experimental results demonstrate that under the normal operating condition (flow rate of 80 mL/min, pressure of 0.7 kgf/cm^2, and temperature of 65 ℃), the potting system maintains stable performance with excellent mixing and curing outcomes. However, the deviation in any single parameter significantly impacts material viscosity balance and the curing reaction, resulting in increasing bubble formation and higher product defect rates. Furthermore, abnormal scenarios were effectively detected in real time by the system, which triggered alerts and visualized trends on the HMI, enabling timely adjustments and maintenance by the operator to prevent low yield rate. In this study, the developed intelligent potting system substantially improves the overall reliability and quality of the manufacturing process. The implementation of predictive maintenance mechanisms further reduces equipment failure rates and unplanned downtimes, thus improving both equipment availability and production efficiency simultaneously.

4.2 Future works

On the basis of the sensor control framework and experimental findings established in this study, several future enhancements and expansions are proposed, as follows.

(1) Multi-parameter interaction analysis: Advanced statistical models such as response surface methodology or principal component analysis can be introduced to evaluate nonlinear interactions among multiple variables and optimize the process more comprehensively.
(2) AI-based anomaly detection and predictive modeling: Machine learning techniques can be adopted to build automated anomaly classification systems and trend forecasting tools, enhancing the system's intelligent decision-making capability.
(3) Database development and cloud integration: By transitioning toward an Industry 4.0 framework, edge computing and cloud platforms may be incorporated to support inter-facility data integration, historical analytics, and remote monitoring.
(4) Application expansion and encapsulation material: Future validation of the proposed system can be conducted on various potting materials (e.g., silicone and polyurethane) and in fields beyond automotive electronics to evaluate its applicability and robustness in diverse application.
(5) Modular control platform development: Designing the sensing and control architecture into modular units will accelerate future equipment development cycles and improve system scalability and maintainability.

In summary, we validated the feasibility and effectiveness of the proposed intelligent potting system in the context of automated dual-liquid processing. Through further advancements in data integration, system intelligence, and modular design, the technology can help achieve highly reliable manufacturing and support the vision of smart factories.

References

1 H. T. Hsueh: Science and Technology Development Observation Platform (June, 2023).
2 Z. M. Mi, W. Y. Wang, W. Y. Chen, and W. H. Chen: Principles and Practical Applications of PLC (Chuan Hwa, Taipei, 2024).
3 European Commission: Regulation (EU) No 661. (Belgium, 2009).
4 Mitsubishi Electric Corporation: MELSEC iQ-F FX5U User Manual - Application Volume (2019).
5 National Highway Traffic Safety Administration: Federal Motor Vehicle Safety Standards (2005).
6 P. Chen and D. Z. Wang: Epoxy Resins and Their Applications (Chemical Industry Press, 2011).
7 J. H. Choi and C. H. An: Sensors **22** (2022) 1785.
8 J. B. Xi, M. Liao, X. W. Teng, C. B. Zheng, H. J. Wang, and J. Huang: CN107617539A. (2017).
9 J. Y. Fan and J. Lin: Science and Technology Policy Research and Information Center (September, 2022).
10 C. Y. Lin: Taiwan Research Highlights (2019) 15.
11 E. Hozdić: Int. J. Mod. Manuf. Technol. **7** (2015) 28.
12 S. Weyer, T. Meyer, M. Ohmer, D. Gorecky, and D. Zühlke: IFAC-PapersOnLine **49** (2016) 97.
13 E. Hofmann and M. Rüsch: Comput. Ind. **89** (2017) 23.
14 C. Shang and F. You: Engineering **5** (2019) 1010.
15 P. Ralston and J. Blackhurst: Int. J. Prod. Res. **58** (2020) 5006.
16 G. Chen, P. Wang, B. Feng, Y. Li, and D. Liu: Int. J. Comput. Integr. Manuf. **33** (2020) 79.
17 Z. Shi, Y. Xie, W. Xue, Y. Chen, L. Fu, and X. Xu: Syst. Res. Behav. Sci. **37** (2020) 607.
18 A. Sanders, C. Elangeswaran, and J. Wulfsberg: J. Ind. Eng. Manage. **9** (2016) 811.

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