IIOT-BASED AUTOMATION: ANNEALING OVEN

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ABSTRACT

The limitations of conventional control systems are becoming more evident as manufacturing process requirements evolve, driven by increasingly complex product requirements and stricter product quality standards. This paper presents an integrated smart automation system that combines Industrial Internet of Things (IIoT) technology with batch management capabilities to address these challenges. The study uses DMAIC methodology to systematically guide the system enhancement efforts combining regression analysis—specifically the coefficient of determination (R-squared or R^2)—to assess the strength of correlation between key process variables. The implementation resulted in 17% increase in oven capacity and 100% improvement in data accuracy. Furthermore, the system significantly reduced product exposure risk during oven malfunctions and doubled end-user awareness. This integration can effectively overcome conventional control limitations while enhancing operational efficiency, product protection, and process reliability in complex manufacturing environments. This work contributes to the advancement of smart manufacturing practices in thermal processing applications.

1. 0 INTRODUCTION

Thermal processing such as annealing is widely used in manufacturing industries, especially in the semiconductor and electronics sectors. Annealing is an important process that helps reduce stress inside a metal or plastic parts, which can affect the performance of the final product. This is done by heating the material to a high temperature—below its melting point—for a certain time, allowing the atoms to move and form new crystal structures[1].

The annealing process, as illustrated in Fig. 1, is characterized by a specific temperature profile over time. It begins with a controlled warm-up phase, allowing the material's composition to gradually adjust to rising temperatures and preventing abrupt atomic displacement. This is followed by the baking phase, where the material is held at a defined temperature for a specific duration to meet the required stress relief specifications. Finally, the cool-down phase allows the material to slowly return to normal conditions, enabling the atoms to settle into a more stable arrangement after heat treatment.

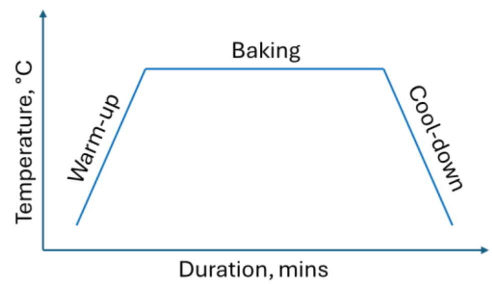

Fig.1 Annealing Process

Despite its critical role, the conventional implementation of annealing in manufacturing environments often falls short in addressing increasingly complex product requirements and ensuring reliable process control. This limitation largely arises from the system's heavy reliance on human judgment, such as operator-dependent control of ovens, manual data entry for traceability, and limited or no integration with available software applications. These factors not only reduce operational efficiency but also increase the risk of human error and data inconsistency.

Moreover, failure to promptly identify equipment malfunctions—such as those involving blower fans, heating elements, thermocouple sensors, or interlocks—can lead to process disruptions, product defects, and increased operational costs. The lack of integrated monitoring and data analytics prevents timely decision-making and increases the risk of human error.

There is a clear need for an intelligent annealing system that incorporates IIoT-enabled real-time monitoring, smart automation, and centralized batch management. It enhances system reliability, improve process control, and support efficient, data-driven operations in high-precision manufacturing environments.

Many researchers from various industries are exploring ways to improve or automate traditional methods, particularly in the annealing process. There is a related study that focuses on reducing costs effectively by implementing smart systems in thermal processing, thereby minimizing the need for direct operator intervention and enhancing both reliability and consistency. The study utilized a Fuzzy-PI with ON/OFF logic control that automates the entire heat treatment process. It used MATLAB/Simulink to test the entire system which includes the control unit, algorithm, sensors, and drive circuits. The results of the study confirm that the automated heat treatment is reliable, as it achieves material hardness with only a ±2HV (Vickers Hardness) difference from traditional process. This is useful in cost reduction and decrease in operator dependency[2].

2. 0 REVIEW OF RELATED WORK

Refer to 1.0 Introduction

3.0 METHODOLOGY

Originally, the annealing oven was equipped with a single thermocouple sensor located near the HEPA filter—outside the actual baking chamber. As a result, the oven's display and control system relied solely on this sensor, which posed a significant limitation in accurately reflecting in-chamber temperature conditions. This makes real-time, visual monitoring of the temperature profile critical for process stability and product quality.

In the original setup, as shown in Fig.2, technicians and operators were required to manually configure a standalone data logger to monitor oven temperature twice daily – every start of shift. This involved physically connecting the device to the oven and positioning it in a suitable location inside the chamber to capture relevant thermal data. Once the baking cycle was complete, technicians had to extract the logged data, typically via USB or SD card, and manually input the temperature readings into an Excel spreadsheet or logbook. This process was not only time-consuming but also introduced a high risk of human error, including misreading values, mistyping entries, or misplacing data files, which could compromise traceability and process validation.

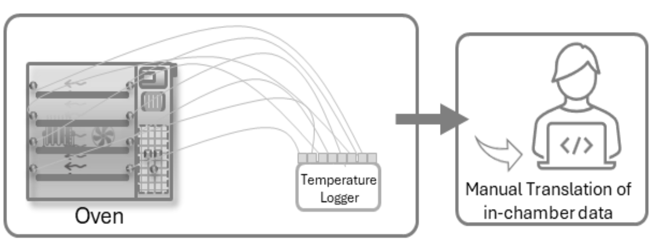

Fig.2 Original temperature monitoring, per shift basis.

The core issue arises when key oven components malfunction, such as a blower fan failure, non-functioning heating elements, a faulty interlock, or a sensor error. To mitigate this risk, the system was upgraded by installing 8 additional thermocouple sensors within the chamber and integrating an additional high-temperature interlock, as illustrated in Fig.3, for improved redundancy and safety.

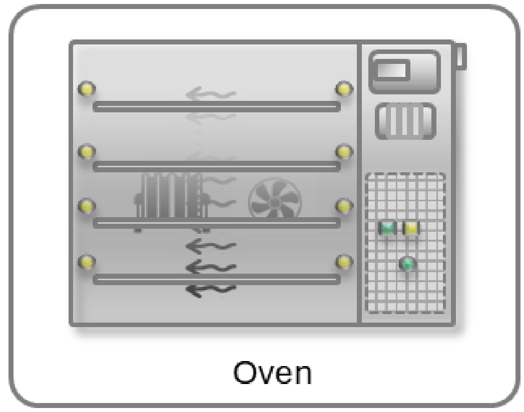

Fig.3 Additional Thermocouple sensor (yellow-circle) and additional high temp interlock (yellow-square). Original thermocouple sensor (green-circle) and original high temp interlock (green-square)

Building upon this hardware upgrade, the first phase of the study involved implementing an Industrial Internet of Things (IIoT)-based solution. The first phase is the introduction of IIoT method where the analog data from sensors are being translated and uploaded to web application where users can monitor and set controls.

In Fig.4, the total of 9 thermocouple sensors (1 built-in and 8 additional) are connected through Moxa I/O Logik to collect analog temperature signals and send it to server computers or controllers prior uploading to a cloud database. The web application then retrieves the data to provide real-time visual monitoring system of temperature profiles, complete with user alert notification when temperature exceeds pre-defined control limits.

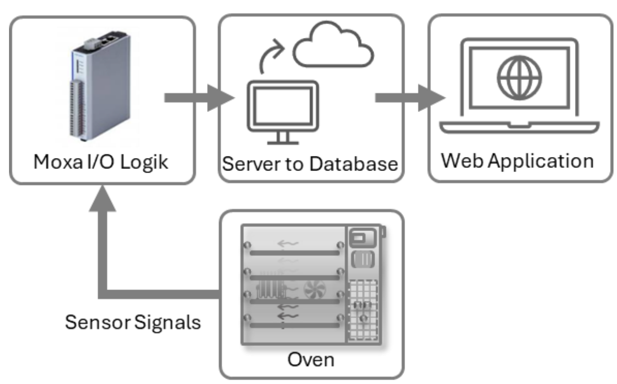

Fig.4 Phase1: Translation of analog signals from oven sensors to web applications (IIoT)

To validate the performance of the IIoT-enabled monitoring system, a regression analysis was conducted comparing the sensor data captured through the in-chamber thermocouple network with the historical readings obtained using the manual data logger. In Fig. 5 and Table 1, it shows the regression analysis between the in-chamber thermocouple sensor and the manual data logger readings. It yields an R-squared (R^2) value of >0.98. This indicates a near-perfect linear correlation, validating the accuracy and reliability of the sensor data captured through the IIoT system.

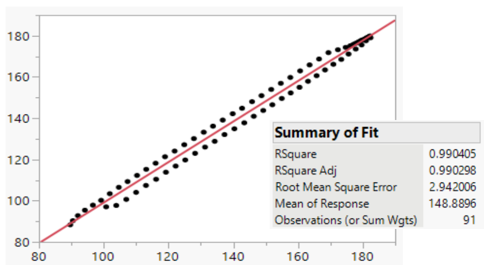

Fig.5 Regression analysis using coefficient of determination (R-squared or R^2). Ave. of 8 chamber sensors (y-axis) vs Ave. of 8 sensors from data logger (x-axis)

Table 1. Coefficient of determination (R-squared or R^2) by temperature sensors

		In-Chamber							
		Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Data Logger	Sensor1	99.81%							
	Sensor2		99.24%						
	Sensor3			99.67%					
	Sensor4				98.41%				
	Sensor5					99.67%			
	Sensor6						98.28%		
	Sensor7							99.96%	
	Sensor8								99.28%

Following the successful implementation of IIoT-enabled thermal monitoring in Phase 1, the second phase of this study focused on advancing operational efficiency through the integration of smart automation and batch management capabilities as shown in Fig.6.

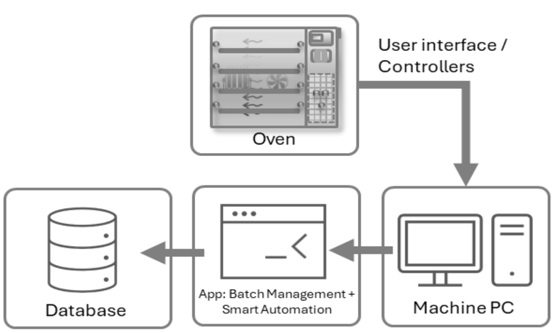

Fig.6 Phase2: Smart automation with batch management

One key component is the Batch Builder Manager, an in-house developed application designed to automate the batching process with built-in error-proofing features. It enforces restrictions based on product-specific requirements—such as predefined recipes or configurations—to ensure accurate and compliant batch execution. In the original setup, batching relied entirely on operator judgment, with no foolproof mechanisms in place. Critical batching data used for traceability was manually logged in Excel spreadsheets, making it prone to human error and mistyping. The Batch Builder application now uses a barcode scanner to log data directly into the system. Once a product is scanned, its corresponding requirements are automatically displayed. If the scanned product does not match the current batch specifications, the system prompts an error—providing operators with an additional layer of verification and improving process awareness.

To complement this, a Smart Automation Application was developed to provide a user-friendly interface, allowing operators to process parts more efficiently. Unlike the traditional oven interface with its small display and manual recipe selection—where oven control was highly operator-dependent—this application simplifies recipe selection and execution. It communicates with the Batch Builder Manager to automatically identify the current batch and apply the corresponding recipe or configuration. Additionally, the Smart Automation Application can integrate with other Manufacturing Execution System (MES) tools, particularly the IIoT web application, to enable real-time data sharing, data uploading, and centralized control.

To fully automate operations, communication pathways were established between the oven, the batch builder system, and associated IIoT and MES platforms. This integration enabled the elimination of manual inputs and significantly improved operational efficiency. The application was designed with ease-of-use in mind to encourage operator engagement and reduce training complexity.

This two-phase methodology enabled the transformation of the annealing process from a manually intensive system to a digitally connected and automated environment. The integration of smart systems not only addressed existing operational risks but also laid the foundation for scalable process improvements.

4.0 RESULTS AND DISCUSSION

This study successfully improved the efficiency and reliability of the annealing process by replacing manual systems with IIoT-based monitoring and smart automation. The implementation was done in two phases and led to major improvements in oven usage, data accuracy, operator workload, and system control.

To ensure proper thermal processing conditions, temperature data through web application is continuously monitored and validated. The latest temperature profile as shown in Fig.7—verified to be free from any sensor anomalies or machine parts malfunctions—serves as the primary reference for operators during daily loading activities. This verified profile ensures that each batch begins under optimal thermal conditions, minimizing the risk of product deviation.

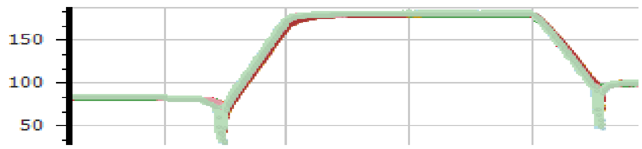

Fig.7 Real-time temperature profile from IIoT application

Furthermore, by eliminating the use of manual data loggers—previously requiring 4 hours per day—the system achieved a 17% increase in oven capacity, contributing significantly to production efficiency.

Overall, the integrated solution transformed the annealing process from a manual, error-prone workflow into a digitally connected, reliable, and efficient operation. A summary of these improvements is shown in Table 2, highlighting the measurable gains achieved through this digital transformation initiative.

Table 2. Benefits of the Project

Metric	Improvement
Oven Capacity	17% increase by eliminating manual logging
Data Accuracy	100% improvement ($R^2 > 0.98$)
Fault Detection	Real-time alerts, safer operations
Traceability	Barcode-based, structured and validated
Response Time	2× improved due to guided interface (Automated prompts, web UI)

5.0 CONCLUSION

The implementation successfully addressed the limitations of conventional control systems by significantly reducing human error, improving data consistency, and enabling proactive anomaly detection. Regression analysis demonstrated the high accuracy and reliability of the sensor data captured through the IIoT system, validating the approach's effectiveness in complex manufacturing environments. These results confirm that IIoT integration represents a viable and valuable enhancement to thermal processing operations, with quantifiable benefits to operational efficiency, product quality, and manufacturing capacity.

6.0 RECOMMENDATIONS

This paper recommends further enhancement of the system algorithm by incorporating predictive maintenance. In the manufacturing industry, certain machines may become sources of delay due to the need for maintenance, calibration, machine repair, or out-of-control signals from sensors. The system can proactively redirect processes away from high-risk or underperforming machines, reducing downtime and improving yield.

7.0 ACKNOWLEDGMENT

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8.0 REFERENCES

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