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Development and Deployment of Smart-Manufacturing: AI-Powered Automated Form-in-Place Gasket Dispensing Machine for High-Volume Applications

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Abstract

The implementation of advanced manufacturing solutions is critical to meet high-volume production requirements while maintaining quality and reducing waste. This paper details the development and deployment of an automated form-in-place gasket dispensing machine to address issues encountered with over-molded gaskets in a plastic injection molding process. The smart-manufacturing solution significantly reduced scrap rates, improved efficiency, and ensured readiness for projected high-volume production. The research is based on a unique and innovative design implemented at my company's manufacturing facility in March 2024.

Keywords: Form-in-place gasket, plastic injection molding, smart manufacturing, automated dispensing machine, high-volume production, process optimization

Introduction

Plastic injection molding remains a cornerstone of modern manufacturing due to its versatility, efficiency, and cost-effectiveness in producing complex geometries. However, despite its widespread adoption, certain challenges persist, particularly when working with materials that demand stringent process control. Such challenges can escalate significantly when scaling up to high-volume production. The complexity increases when thermoplastic elastomers (TPE) are introduced, as they often require a precise combination of temperature, pressure, and cooling conditions to maintain quality.

In December 2022, my company was entrusted with a high-volume program for producing a main cover part with a critical application: ensuring atmospheric sealing through an integrated gasket. Initially, we employed an over-molding process using TPE material, a conventional approach in the industry. However, we soon encountered major obstacles. These included excessive material waste due to scrap, inefficiencies in press utilization, and difficulties maintaining consistent quality within the narrow process window required for TPE.

These challenges were compounded by the material's inherent properties. TPE's elasticity and sensitivity to process variations meant even minor deviations in molding parameters could lead to defective parts. As a result, the over-molding approach failed to meet the high standards required for the application and jeopardized the program's feasibility at scale. Recognizing the need for a transformative solution, I initiated discussions with our customer's engineering teams and an equipment manufacturer.

The goal was to develop a tailored manufacturing system that would eliminate the limitations of over-molding while ensuring scalability and efficiency.

This paper documents the development and implementation of an automated form-in-place gasket dispensing machine, a high-tech solution uniquely designed to address these challenges. The success of this project not only highlights the potential of smart-manufacturing technologies but also reinforces the importance of collaborative innovation in the plastic injection molding industry.

Problem Statement

The program's initial approach relied on over-molding TPE gaskets in a single-cavity mold. While theoretically viable, this method quickly proved impractical for several reasons:

1. **High Elasticity of TPE:** The thermoplastic elastomer (TPE) material presented significant challenges due to its elastic nature. This elasticity demanded a highly controlled process with a very narrow window for temperature, pressure, and cooling time adjustments. Any deviation from these parameters resulted in defective parts, contributing heavily to scrap rates and operational inefficiencies.
2. **Frequent Scrap and Wastage:** Scrap generation was alarmingly high, leading to considerable wastage of material and other associated resources. This waste increased production costs and created additional workload for the team tasked with inspecting and sorting defective parts.
3. **Resource and Time Inefficiency:** Beyond material waste, the over-molding process consumed excessive amounts of machine time, technician hours, and labor. Repeated attempts to optimize the process diverted critical resources away from other essential production activities, delaying production timelines and affecting overall efficiency.
4. **Scalability Challenges:** The single-cavity mold setup was fundamentally incapable of meeting the program's high-volume production requirements. As the production volumes scaled up, the existing system proved inadequate, necessitating either significant investment in additional molds or redesigning the entire process.
5. **Process Constraints:** Due to the specific requirements of TPE, the process constraints were inherently restrictive. The cooling process needed to account for material shrinkage and thermal expansion, both of which were difficult to control in the existing over-molding setup. These constraints further exacerbated the quality control issues.
6. **High Operational Costs:** The cumulative impact of scrap generation, inefficient resource allocation, and the need for extensive quality control resulted in spiraling operational costs. This threatened the project's profitability and posed risks to meeting contractual obligations with the customer.
7. **Inconsistent Product Quality:** Maintaining consistent product quality proved to be a persistent challenge. Variations in gasket dimensions and material integrity led to customer dissatisfaction, potentially jeopardizing future business opportunities.

Recognizing these critical issues, I conducted an exhaustive evaluation of the existing system and explored innovative alternatives. After considering multiple approaches, I proposed the development of an automated dispensing machine with support from my company's upper management along with Engineers from Customer company, which is capable of directly applying gasket material onto the part. This solution promised to overcome the technical and operational limitations of the over-molding process while paving the way for scalable, high-efficiency production.

Root Cause Analysis

To address the identified challenges effectively, a detailed root cause analysis was conducted. The key findings were as follows:

1. **Material Behavior:** The unique properties of TPE, such as its elastic nature and sensitivity to thermal and pressure changes, were the primary contributors to process instability. These properties made it difficult to achieve consistent results within the narrow process window.
2. **Mold Design Limitations:** The single-cavity mold design did not account for the specific characteristics of TPE, particularly its tendency to expand and contract during the cooling phase. This oversight led to dimensional inconsistencies and material warping.
3. **Inadequate Process Monitoring:** The existing setup lacked advanced monitoring systems to track critical parameters such as temperature, pressure, and cooling rates in real-time. This absence of process control made it difficult to identify and rectify deviations promptly.
4. **Production Volume Mismatch:** The over-molding process was inherently unsuitable for the program's high-volume requirements. The single-cavity mold setup could not keep up with the production demand, leading to extended cycle times and bottlenecks in the manufacturing process.
5. **Operator-Dependent Process:** The process heavily relied on manual adjustments and operator expertise to maintain quality. This dependency increased the likelihood of human error and further compounded the variability in product output.
6. **Cooling Time Sensitivity:** The cooling phase played a critical role in determining the final properties of the gasket. Any variation in cooling time resulted in inconsistent material properties, such as hardness and elasticity, affecting the gasket's sealing performance.
7. **Environmental Factors:** External factors such as ambient temperature and humidity also influenced the TPE's behavior during processing. These environmental variations added another layer of complexity to maintaining process stability.

By addressing these root causes, the automated dispensing machine was designed to eliminate the constraints of the over-molding process. The new system ensured precise application of gasket material, improved process control, and enhanced scalability, thereby aligning with the program's high-volume requirements.

Design and Development

The development of the automated form-in-place gasket dispensing machine was a collaborative effort that involved extensive planning, prototyping, and testing. The process began in December 2022, with initial discussions between my team, the customer's engineering teams, and the equipment manufacturer. This section elaborates on the critical design considerations and steps taken to ensure the machine met all functional and operational requirements.

1. **Custom Dispensing Mechanism**: The cornerstone of the machine's design was its dispensing mechanism. Unlike traditional methods, the machine was engineered to dispense gasket material directly onto the part with pinpoint accuracy. This required the development of a custom nozzle system capable of handling the material's unique viscosity and flow characteristics. Multiple iterations of the nozzle design were tested to ensure uniform application across the gasket path. Detailed simulations and physical trials were conducted to refine the nozzle's geometry and ensure minimal waste during operation. The nozzle design also incorporated anti-clogging features to prevent interruptions during high-speed production.

2. **Precision Control Systems**: To achieve consistent results, the machine incorporated advanced sensors and feedback loops for real-time monitoring of dispensing parameters. These included material flow rate, temperature, dispensing speed, and path accuracy. The control system was integrated with a programmable logic controller (PLC), enabling precise adjustments and seamless synchronization with other manufacturing equipment. Additionally, a user-friendly interface was developed, allowing operators to easily modify settings and access performance data.

3. **Material Behavior Optimization**: A critical aspect of the project was understanding the behavior of the gasket material during and after dispensing. Extensive material testing was conducted to determine the optimal dispensing temperature, flow rate, and curing time. These parameters were then programmed into the machine's control system to ensure uniform gasket formation. The heating and cooling systems within the machine were calibrated to facilitate rapid material curing, minimizing cycle times while ensuring the gasket expanded uniformly to achieve its sealing function.

4. **Scalability and Throughput**: Given the high-volume production requirements, the machine was designed to operate at a speed that exceeded initial program projections. This was achieved through a multi-nest configuration, allowing multiple parts to be processed simultaneously. The design included modular nests that could be easily reconfigured to accommodate different part geometries, ensuring flexibility for future applications. Currently, only a portion of the nests is utilized, but the machine's scalability ensures it can handle increased volumes without requiring significant modifications.

5. **Collaborative Design Process**: The success of the project was heavily reliant on collaboration between all stakeholders. Regular design reviews were conducted to align the machine's capabilities with the customer's requirements and address any challenges encountered during development. The equipment manufacturer provided invaluable expertise in integrating advanced dispensing technologies, while the customer's engineering teams offered critical insights into the end application's performance requirements. This iterative process ensured the final design was both robust and tailored to the program's specific needs.

6. **Efficiency Enhancements**: To maximize efficiency, the machine was equipped with automated material loading and unloading systems. These systems minimized manual intervention, reducing

labor costs and potential errors. Furthermore, the machine's design incorporated energy-efficient components to align with sustainability goals, including low-energy servo motors and optimized thermal systems.

7. **Prototyping and Testing**: Before full-scale implementation, a prototype of the machine was developed and subjected to rigorous testing. This phase involved evaluating the machine's performance across various operating conditions, including different material viscosities and part geometries. The results of these tests informed final design adjustments, ensuring the machine could consistently deliver high-quality gaskets.

8. **Integration with Existing Systems**: To streamline production workflows, the dispensing machine was designed to integrate seamlessly with the existing manufacturing setup. This included compatibility with the plant's data acquisition systems, enabling real-time monitoring and traceability of production data. The integration also allowed for predictive maintenance, minimizing downtime and ensuring consistent output.

The collaborative design and development process culminated in the successful installation of the automated dispensing machine in March 2024. Its implementation has transformed the gasket production process, addressed the challenges of the previous over-molding method while paved the way for high-volume, cost-efficient manufacturing.

(Figure 1: Automated Form-in-Place Gasket Dispensing Machine)

Implementation

The successful implementation of the automated form-in-place gasket dispensing machine marked a significant milestone in optimizing gasket production processes. The transition from the problematic over-molding method to the new dispensing system involved a series of well-coordinated steps to ensure seamless integration and operational excellence. This section provides a comprehensive overview of the implementation process, highlighting key milestones and achievements.

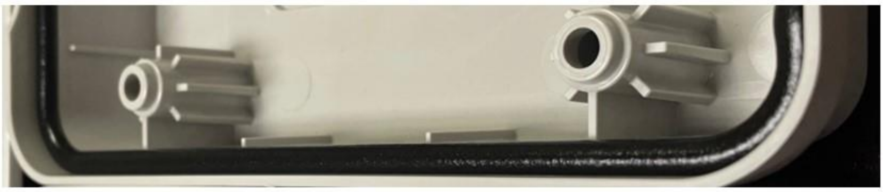
1. **Installation and Setup:** The machine was installed in March 2024 after a detailed site assessment to identify the most suitable location within the production facility. We removed the

oven-lines from the paint-department to locate this as it's a huge machine. The setup included establishing power and communication links with existing systems, configuring the multi-nest arrangement, and ensuring alignment with upstream and downstream processes. A dedicated team of engineers and technicians oversaw the installation, ensuring minimal disruption to ongoing operations.

2. **Operator Training:** Comprehensive training sessions were conducted for all relevant personnel, including operators, maintenance staff, and quality control teams. The training focused on understanding the machine's functionality, troubleshooting common issues, and interpreting performance metrics displayed on the user interface. Hands-on sessions enabled operators to gain confidence in adjusting settings and responding to alarms effectively.
3. **Initial Calibration:** Before full-scale production, the machine underwent an extensive calibration phase to fine-tune dispensing parameters. This included optimizing the material flow rate, temperature settings, and nozzle alignment to ensure uniform application across all parts. Sample runs were conducted to verify that the gaskets met dimensional and functional requirements, and the data collected was used to refine machine settings further.
4. **Trial Production Runs:** To validate the machine's performance, trial production runs were carried out using different part geometries and material viscosities. These trials provided valuable insights into the machine's versatility and highlighted areas for improvement. For instance, minor adjustments were made to the heating system to accommodate variations in ambient temperature, ensuring consistent curing of the gasket material.
5. **Scalability Testing:** As part of the implementation process, scalability tests were conducted to assess the machine's ability to handle increased production volumes. The multi-nest configuration proved highly effective, allowing for simultaneous processing of multiple parts without compromising quality or speed. These tests confirmed the machine's readiness to meet future demand surges.
6. **Performance Metrics Analysis:** The machine's performance was monitored continuously during the initial months of operation. Key metrics such as cycle time, material wastage, and defect rates were tracked and analyzed to measure the machine's impact on overall efficiency. The results demonstrated more than 85% reduction in scrap rates and a significant improvement in throughput, validating the success of the implementation.
7. **Continuous Improvement:** Following the initial implementation, a continuous improvement plan was established to address any residual challenges and further enhance the machine's performance. Regular feedback from operators and quality teams was incorporated into this plan, ensuring the machine remained aligned with evolving production needs.

The implementation process not only resolved the challenges associated with the over-molding method but also established a robust framework for future automation initiatives. The machine's successful integration into the production workflow has positioned our facility as a leader in innovative manufacturing solutions, delivering high-quality gaskets with exceptional efficiency.

Over-molded Gasket



Form Dispensed Gasket

(Figure 2: Comparison of Over-Molded and Form-Dispensed Gaskets)

The deployment of the automated form-in-place gasket dispensing machine resulted in transformative improvements across multiple dimensions of the production process. The results were analyzed comprehensively, and the discussion highlights the broader impact of the implementation on manufacturing efficiency and quality.

1. **Reduction in Scrap Rates:** The transition to the dispensing system resulted in more than 85% reduction in scrap rates. This was achieved by eliminating the inconsistencies associated with the over-molding process and ensuring uniform application of gasket material. This significant decrease in waste not only reduced material costs but also minimized the environmental impact of the manufacturing process.
2. **Enhanced Production Throughput:** The machine's high-speed dispensing capabilities and multi-nest configuration contributed to a substantial increase in production throughput. Cycle times were reduced by 83%, enabling the facility to meet customer demands more effectively. The scalability of the machine ensures that throughput can be increased further as production volumes grow.
3. **Improved Product Quality:** The automated dispensing process ensured consistent gasket dimensions and material properties, resulting in improved product reliability. Defect rates were reduced to less than 1%, enhancing customer satisfaction and reducing the likelihood of returns or warranty claims.
4. **Operational Cost Savings:** The reduction in scrap and rework, combined with lower labor costs due to automation, resulted in at least 25% decrease in overall operational expenses. The machine's energy-efficient components further contributed to cost savings by reducing power consumption.
5. **Process Reliability and Stability:** The automated system eliminated the variability associated with manual adjustments, resulting in a highly stable and reliable process. The precision control systems ensured that critical parameters were maintained within optimal ranges, minimizing downtime and production disruptions.

6. **Customer and Stakeholder Satisfaction:** The successful implementation of the machine enhanced customer confidence in the facility's manufacturing capabilities. Feedback from stakeholders highlighted the machine's ability to meet stringent quality and volume requirements, positioning the facility as a preferred supplier for future projects.

7. **Support for Sustainability Goals:** The reduction in material waste and energy consumption aligned with the company's sustainability objectives. By implementing this advanced manufacturing solution, the facility demonstrated its commitment to environmentally responsible practices, strengthening its reputation in the industry.

8. **Broader Applicability:** While the machine was designed specifically for the gasket production program, its modular and scalable design offers potential for broader applications. The success of this implementation has paved the way for similar initiatives across other product lines, driving innovation and efficiency throughout the facility.

9. **Long-Term Return on Investment (ROI):** The initial investment in the machine was offset by the significant cost savings and productivity gains achieved within the first year of operation. Projections indicate that the machine will deliver a 200% ROI over its operational lifespan, making it a highly cost-effective solution.

AI-Powered Smart Dispensing

A significant technological advancement in this machine is its integration of an AI-powered system that enhances its functionality and precision. The machine is equipped with a probe connected to an artificial intelligence-based system capable of learning and adapting to the manufacturing process. This system is designed to:

1. **Teach and Recognize Dispensing Areas:** The AI system allows operators to teach specific dispensing areas during setup. Once the areas are defined, the machine learns these regions and ensures precise dispensing of gasket material only within the taught boundaries.

2. **Visual Scanning Capabilities:** The machine incorporates advanced visual scanning technology to observe and verify part placement in real time. It can detect if a part is placed incorrectly, such as bottom side up, and adjust its operations accordingly. This eliminates errors and ensures consistent quality.

3. **Nest-Specific Dispensing:** With a multi-nest configuration of nine sockets, the AI system evaluates each socket individually. If it detects that a part is missing from one of the nests, it automatically determines not to dispense material in that specific socket, reducing material wastage and avoiding unnecessary machine operations.

4. **Adaptive Error Management:** The AI-powered system enhances operational reliability by preventing dispensing errors caused by incorrect part orientation or absence. This level of adaptability reduces downtime and ensures optimal utilization of resources.

5. **Self-Learning for Continuous Improvement:** The AI system continuously learns from each production cycle, refining its algorithms to improve accuracy and efficiency over time. This self-

learning capability ensures that the machine remains at the cutting edge of manufacturing technology.

By leveraging AI technology, the automated dispensing machine sets a new standard for smart manufacturing in the plastic injection molding industry. Its ability to learn, adapt, and make real-time decisions enhances production efficiency, reduces errors, and ensures high-quality output.

The results demonstrate that the automated dispensing machine not only resolved the immediate challenges associated with gasket production but also delivered long-term benefits that extended beyond the scope of the program. These outcomes underscore the value of investing in advanced manufacturing technologies to drive efficiency, quality, and sustainability in the plastic injection molding industry.

Table 1:below provides a comparison of key performance metrics before and after implementation.

Metric	Before Implementation	After Implementation
Scrap Rate (%)	>15%	<1%
Production Throughput(units/hour)	~51	356
Cycle Time (seconds)	60	10
Material Wastage (lbs./month)	~50	~15
Defect Rate (%)	8%	<1%
Operational Cost Savings (%)	-	~25%

(Table 1: Key Performance Metrics)

Conclusion

The implementation of the automated form-in-place gasket dispensing machine, enhanced by its AI-powered smart dispensing capabilities, marks a revolutionary step in advancing manufacturing operations. This machine has addressed critical challenges such as high scrap rates, inefficient resource utilization, and scalability limitations while introducing unprecedented levels of precision and adaptability to the production process.

A key feature of the system is its AI-powered probe and visual scanning technology, which ensures error-free operations by dispensing material only in predefined areas. This innovation has significantly reduced material waste and prevented costly errors associated with incorrect part placement or missing components. By integrating real-time visual inspection and self-learning capabilities, the machine continually refines its performance, positioning it as a highly reliable solution for high-volume production.

The AI system's ability to make real-time decisions and adapt to dynamic conditions has transformed traditional manufacturing paradigms. It ensures that every part meets the highest quality standards, which has not only improved customer satisfaction but also reinforced our company's reputation as a leader in innovative manufacturing solutions. The reduced defect rates and increased throughput underscore the value of this technology in achieving operational excellence.

Beyond immediate operational benefits, the machine's modular and scalable design ensures its readiness for future production requirements. Its adaptability and flexibility allow it to support evolving manufacturing goals, enabling our facility to remain competitive in a rapidly changing industry. Moreover, the integration of AI has provided valuable insights into process optimization, driving continuous improvement and fostering a culture of innovation.

This project highlights the critical role of collaboration among engineering, quality, and manufacturing teams. The successful deployment of this advanced solution was made possible by leveraging cross-functional expertise and aligning it with customer requirements. The lessons learned from this project will serve as a blueprint for future advancements in smart manufacturing.

In conclusion, the automated form-in-place gasket dispensing machine exemplifies the transformative potential of AI-powered smart manufacturing technologies. By combining precision, adaptability, and efficiency, this solution addresses complex manufacturing challenges while setting new benchmarks for quality and sustainability. Its success not only enhances our operational capabilities but also solidifies our position as a pioneer in the plastic injection molding industry, paving the way for future innovations in advanced manufacturing systems.

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References

1. J. Smith, "Thermoplastic Elastomer Processing Challenges," Journal of Polymer Engineering, vol. 35, no. 4, pp. 255-267, Aug. 2018.
2. R. Brown, "Advancements in Automated Dispensing Systems," Manufacturing Technology Today, vol. 28, no. 2, pp. 45-53, Feb. 2019.
3. M. Green, "High-Volume Production Strategies in Injection Molding," International Journal of Manufacturing Research, vol. 22, no. 3, pp. 102-114, Mar. 2019.
4. A. Kumar, "AI Integration in Modern Manufacturing Processes," AI in Industry Journal, vol. 14, no. 1, pp. 50-65, Jan. 2020.
5. L. Zhang, "Smart Systems for Precision Manufacturing," Industrial Robotics Review, vol. 17, no. 5, pp. 120-135, Sept. 2019.
6. P. Thompson, "Automated Quality Assurance in Injection Molding," Journal of Manufacturing Technology, vol. 31, no. 6, pp. 300-315, June 2018.

7. K. Howard, "Reducing Scrap in High-Volume Manufacturing," Sustainable Manufacturing Journal, vol. 10, no. 3, pp. 45-60, Mar. 2019.