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ADVANCED ERROR-PROOFING IN PLASTIC INJECTION MOLDING: IMPLEMENTING A SECONDARY HOLE-MAKING OPERATION TO PREVENT MOLD PIN BREAKAGE THROUGH HYDRAULIC MOTOR OPERATION AND SEQUENCING ERROR

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Abstract

In November 2021, a critical issue involving injection mold pin breakage arose during the production of cover parts with pre-designed holes for wire passage. These holes were initially made in-mold using pins actuated by hydraulic cylinders. However, due to machine sequencing limitations, the press occasionally closed on the mold before retracting the pins, causing breakages. This repeated failure led to significant downtime, production delays, and increased repair costs. To address the issue, a secondary assembly machine was developed to create these holes post-molding, eliminating the risk of pin breakage. This paper discusses the root cause analysis, the collaborative development process with automation partners, and the successful implementation of this solution. The introduction of error-proofing measures and a robust quality assurance system in the new setup has enhanced production reliability, reduced maintenance costs, and strengthened customer confidence. These advancements underscore the importance of innovative approaches in solving complex manufacturing challenges.

Keywords Plastic Injection Molding, Pin Breakage, Hole-Making Operation, Automation, Secondary Operations, Error-Proofing

I. INTRODUCTION

In the high-precision world of plastic injection molding, manufacturers are often required to deliver intricate parts with specific design features to meet customer requirements. Among these features are holes and channels that allow for the passage of wiring or other components in downstream assemblies. These design elements, while critical, can introduce substantial challenges during the molding process, especially when integrated directly into the mold. Hydraulic cylinder systems, commonly used in injection molding, have been extensively studied for their precision and operational limitations. These limitations, as highlighted by the Engineering Toolbox (2019), can affect the reliability of mold-actuated mechanisms [10].

For this project, the initial design approach involved creating holes for wire passage directly within the injection mold using retractable pins. These pins, operated by hydraulic cylinders, were intended to retract at specific intervals during the molding cycle to allow for clean ejection of the molded part. However, due to limitations in the press machine's sequencing capabilities, this approach encountered operational setbacks. Specifically, the machine was unable to control each hydraulic pin's sequence independently, leading to instances where the mold closed before the pins fully retracted. Such incidents caused the pins to break within the mold, resulting in costly damage, production downtime, and significant delays. Sequencing limitations in hydraulic cylinder systems are a known source of operational inefficiency in manufacturing, as observed by Gu and Yan (2019) [1].

This challenge became especially pressing when a customer was present at the facility to witness the mold trial. Machine downtime during critical demonstrations interrupted production and affected the ability to demonstrate a reliable manufacturing process. Downtime caused by recurring equipment failures, as noted by Toyo and Tanaka (2019), can significantly impact customer satisfaction and production schedules, leading to reputational risks [6].

The combination of these factors highlighted an urgent need for a solution that would eliminate this recurring issue and enhance the reliability of the production process. To address this problem, alternative methods to incorporate hole-making as a secondary operation rather than relying on retractable pins within the mold were explored. The adoption of secondary operations, such as automated assembly machines, has been recognized as a viable solution to reduce risks in injection molding processes, as suggested by Li and Roberts (2017) [5].

This shift in approach not only promised to eliminate the risk of pin breakage but also presented an opportunity to streamline the manufacturing process, reduce maintenance costs, and meet customer expectations more consistently. The solution ultimately involved designing a dedicated assembly machine to create these holes as a secondary operation post-molding. This machine introduced advanced error-proofing techniques, such as part presence sensors, to further improve process reliability and product quality, aligning with the recommendations of Rolfes and Buchanan (2018) [7].

This paper discusses the root causes of the initial issue, the collaborative development process with an automation company, and the successful implementation of the assembly machine, which resolved the pin breakage issue and enhanced production reliability. By embedding robust error-proofing measures into the new solution, the project not only met stringent quality requirements but also set a benchmark for innovative approaches in plastic injection molding.

II. PROBLEM STATEMENT

The problem at hand was a repeated failure of mold-integrated pins used to create holes in a plastic injection-molded cover part. The original design leveraged retractable pins, actuated by hydraulic cylinders, to form these holes during the molding process. However, the press machine's sequencing limitations led to two separate incidents where the mold closed prematurely on the extended pins, causing breakage. Such failures are not uncommon in complex manufacturing systems and have been documented as critical risks in the optimization of injection molding processes, as noted by Zhang and Miller (2020) [3].

Each pin breakage incident required extensive downtime for repairs, causing significant delays in production and adding considerable repair costs to the project. Moreover, downtime caused by recurring equipment failures can have far-reaching implications. Studies by Toyo and Tanaka (2019) highlight how frequent disruptions not only affect production schedules but also increase operational expenses, impacting an organization's profitability and reliability in the market [6].

Furthermore, these breakdowns disrupted production during critical customer visits, potentially impacting on our relationship and reputation with key clients. Customer perception of manufacturing reliability is a vital component of competitive advantage in the plastic injection molding industry. As Gu and Yan (2019) have emphasized, maintaining consistent production performance during high-stakes demonstrations is essential to securing customer trust [1].

This problem was not only technically challenging but also financially unsustainable. Each pin breakage incident involved costly repairs to the mold and the hydraulic system, contributing to increased maintenance expenses and unplanned interruptions in the production schedule. The financial burden of such repeated failures is further compounded by reputational damage. According to Juran and Godfrey (1998), customer dissatisfaction stemming from delayed deliveries can result in long-term harm to business relationships [4].

The failure to reliably produce parts under these conditions highlighted a significant risk for our business, as recurring breakdowns could result in lost customer confidence and a negative impact on our company's reputation in the market. This aligns with the observations of Kim and Wang (2018), who noted that manufacturers operating under tight deadlines and complex requirements must prioritize error-proofing and process optimization to mitigate risks [2].

In light of these challenges, it became clear that a robust solution was essential to maintain production efficiency and safeguard the integrity of our customer relationships. Collaborating closely with our tooling and automation teams, we explored alternative solutions that would allow us to overcome the limitations of mold-integrated pins. The concept of performing wire-passage hole creation as a secondary operation emerged as a promising approach. Secondary operations, as demonstrated in the studies of Li and Roberts (2017), are effective in addressing design and process limitations while enhancing overall system reliability [5].

By eliminating the need for mold-integrated pins, we aimed to prevent further damage to the mold, ensure continuous production, and avoid the costly downtime that had previously disrupted our operations. This approach not only promised technical feasibility but also aligned with the industry's emphasis on using automation to improve manufacturing efficiency, as highlighted by Rolfes and Buchanan (2018) [7]. This paper details the development and successful deployment of this error-proofing solution, which has since become a valuable asset in our manufacturing process.

III. ROOT CAUSE ANALYSIS

The root cause analysis revealed that the pin breakage issue stemmed from an inability of the press machine to control individual pin retraction sequences within the mold. In the initial setup, these pins were actuated by a hydraulic cylinder system designed to retract at specific intervals during the injection molding process, allowing for the seamless formation of wire-passage holes within the cover part. Hydraulic systems, while critical for precision operations, are often limited by their dependency on synchronized timing mechanisms within the press machine. As Gu and Yan (2019) observed, such systems are prone to operational inefficiencies when timing mismatches occur in high-complexity manufacturing setups [1].

The hydraulic system relied on the press machine's timing mechanism to ensure each pin retracted to its home position before the mold closed. However, due to the limitations in the sequencing capabilities of the press machine, precise control of pin retraction was not achievable. Instances where the mold closed while one or more pins were still extended resulted in significant mechanical stress, ultimately leading to pin breakage. This aligns with findings by Engineering Toolbox (2019), which noted that hydraulic systems without advanced timing controls are susceptible to failure under conditions of high load or misalignment [10].

Each breakage incident not only required replacement of the damaged pins but also involved repairs to the mold itself. These repairs added both time and cost burdens to the production process, further straining operational resources. The financial implications of repeated breakdowns in injection molding systems have been highlighted by Zhang and Miller (2020), who identified tool damage and maintenance delays as critical contributors to increased production costs [3].

Moreover, the inability of the press machine to ensure precise pin retraction with 100% reliability exposed a significant gap in the current error-proofing measures. While the initial design was technically feasible, it lacked robust safeguards to prevent the mold from closing on extended pins. This deficiency underscored the importance of incorporating advanced fail-safes to eliminate such risks. Juran and Godfrey (1998) emphasized that robust error-proofing measures are essential for maintaining process reliability and minimizing the risk of recurring failures [4].

The recurring pin breakages also disrupted the manufacturing schedule, leading to unplanned downtime and delays in meeting delivery commitments. The cumulative effect of these disruptions posed significant risks to customer relationships and production timelines, as noted in studies by Toyo and Tanaka (2019) [6]. During critical customer visits, these failures also impacted the company's reputation, further emphasizing the need for a reliable and error-proof solution.
This realization drove an exploration of alternative methods to eliminate the risks associated with mold-integrated pins while maintaining high-quality production standards. Secondary operations, such as the use of independent assembly machines, have been identified as effective approaches to addressing similar challenges in advanced manufacturing environments. As Li and Roberts (2017) demonstrated, integrating secondary operations can mitigate risks associated with primary manufacturing processes while improving overall system efficiency [5].

In summary, the root cause of the pin breakage issue was the press machine's inability to synchronize the hydraulic system's pin retraction mechanism with the mold closure sequence. This limitation, combined with the absence of robust fail-safes, led to recurring mechanical failures, increased maintenance costs, and disrupted production schedules. By addressing these root causes through the implementation of a dedicated assembly machine, the process was transformed into a more reliable and efficient operation. As Rolfes and Buchanan (2018) highlighted, incorporating automation and error-proofing technologies not only resolves technical challenges but also enhances the overall reliability of manufacturing systems [7].

IV. PREVENTIVE SOLUTIONS

Recognizing the need to eliminate the risk of pin breakage, a detailed investigation into alternative hole-making techniques that did not rely on mold-integrated pins was initiated. The initial step involved collaborating with tooling and automation teams to analyse various secondary operation methods that could achieve the same hole-making objectives outside of the injection molding process. Secondary operations have been widely recognized as a practical solution to overcome design and process limitations in manufacturing, as noted by Li and Roberts (2017) [5].

Through these discussions, it became clear that an independent assembly machine could serve as a viable solution, allowing the hole-making operation to be performed as a post-molding step, entirely separate from the mold itself. This separation of processes not only promised to eliminate the risk of pin breakage but also allowed for enhanced control over hole placement and quality. Zhang and Miller (2020) emphasized that post-molding operations provide greater precision and repeatability in manufacturing processes, making them a preferred choice in high-reliability industries [3].

During the evaluation phase, several key benefits of this approach were identified. First, removing the pins from the mold streamlined the mold design, simplifying maintenance requirements and reducing the potential for mechanical failures. Studies by Gu and Yan (2019) have shown that simplifying mold structures reduces maintenance costs and extends tool lifespan, offering long-term operational benefits [1]. Additionally, by isolating the hole-making operation, the assembly machine could maintain consistent quality across each part, regardless of the specific configurations within the injection mold.

To address the risk of unintended drilling cycles or safety issues, light-curtains were incorporated into the assembly machine design as the primary error-proofing mechanism. These light-curtains were programmed to allow the machine to cycle only when the light beams remained uninterrupted. If an operator or any object obstructed the light-curtain beams, the machine would immediately lock out, ensuring that the drilling process only initiated under safe conditions. Rolfes and Buchanan (2018) emphasized the effectiveness of light-curtain systems in preventing unintended operations in automated manufacturing environments [7].

To further stabilize the parts during the drilling operation, hydraulic-actuated clamps were integrated into the assembly machine. These clamps ensured that each part was securely positioned before the drilling cycle began, providing stability and reducing the risk of misalignment. Toyo and Tanaka (2019) noted that clamping mechanisms are critical in automated systems to maintain accuracy and precision during operations [6].

Furthermore, the new approach allowed for greater flexibility in meeting customer specifications. By transitioning to a post-molding hole-making operation, adjustments to hole dimensions or positions could be implemented with minimal disruption to the production process. This adaptability aligns with industry recommendations for scalable and future-proof manufacturing solutions, as discussed by Li and Roberts (2017) [5].

In summary, the preventive solution involved transitioning from a mold-integrated approach to a secondary operation using an assembly machine designed specifically for high-precision hole-making. The incorporation of light-curtains as a fail-safe mechanism and hydraulic clamps for part stability addressed the key challenges of the previous process. This solution not only eliminated the risk of pin breakage but also introduced robust error-proofing measures, streamlined maintenance, and enhanced production flexibility. As Rolfes and Buchanan (2018) noted, integrating automation and safety features into manufacturing processes is a critical step toward achieving greater reliability and efficiency [7].

V. CORRECTIVE ACTION

The corrective action phase focused on designing, testing, and deploying a secondary assembly machine to create wire-passage holes as a post-molding operation. This solution directly addressed the root cause of the pin breakage incidents by eliminating the reliance on mold-integrated pins. As Li and Roberts (2017) demonstrated, secondary operations provide an effective means of mitigating risks associated with primary processes, such as mechanical failures during molding [5].

To develop this customized assembly machine, close collaboration with a trusted automation company was critical. The machine was tailored specifically for the requirements of our production process, incorporating advanced control features to maintain tight tolerances on hole placement and diameter. Custom machinery design for specialized manufacturing processes has been identified by Gu and Yan (2019) as an essential strategy for enhancing product quality and reliability in high-precision industries [1].

The assembly machine was engineered to deliver precision and reliability while addressing the operational challenges of the previous mold-integrated approach. To prevent unintended drilling cycles and ensure operator safety, light-curtains were integrated into the machine. These light-curtains acted as a fail-safe mechanism, locking out the drilling cycle if the beams were interrupted. By programming the machine to cycle only when the light beams remained unbroken, the risk of unsafe or erroneous operations was effectively eliminated. Rolfes and Buchanan (2018) underscored the importance of light-curtains as a proven safety solution for automated manufacturing systems [7].

Additionally, hydraulic-actuated clamps were installed to stabilize the parts during the drilling operation. These clamps ensured that each part was securely positioned, reducing the risk of misalignment or movement during the drilling process. Toyo and Tanaka (2019) highlighted the role of robust clamping systems in maintaining precision and improving the reliability of post-molding operations [6].

The assembly machine also included a quality verification process post-drilling. This system allowed for the inspection of each completed hole for dimensional accuracy and positioning relative to design specifications. Although pre-drilling alignment confirmation was not available, the post-drilling quality assurance system provided robust control over the final product. Zhang and Miller (2020) emphasized that post-operation quality verification is critical for ensuring high standards in advanced manufacturing processes [3].
Customer involvement during the review and validation process further validated the machine's

performance. The customer was invited to observe a trial run of the new setup, during which they witnessed the machine's precision, safety features, and seamless integration of the hydraulic clamping system. Positive feedback from the customer reinforced the value of this solution, as it aligned with their quality expectations and operational requirements. Liao and Wu (2020) stressed that customer collaboration during the implementation phase builds trust and ensures alignment between production capabilities and client needs [9].

In summary, the corrective action focused on replacing the mold-integrated hole-making process with a post-molding operation using a dedicated assembly machine. By incorporating light-curtains as a safety mechanism and hydraulic clamps for part stabilization, the solution addressed previous challenges while enhancing safety, precision, and operational reliability. As Rolfes and Buchanan (2018) observed, integrating robust automation technologies into manufacturing systems not only resolves immediate technical challenges but also ensures long-term operational excellence and quality [7].

Figure 1: Assembly machine I got developed for post-molding hole-making operation.

VI. IMPLEMENTATION PROCESS

The implementation of the secondary hole-making assembly machine was a multifaceted process involving multiple stages of design, testing, validation, and integration. Each step was carefully planned and executed to ensure that the final solution met our quality and operational standards, aligned with customer requirements, and permanently resolved the pin breakage issue. Gu and Yan (2019) emphasized that a systematic and iterative approach to process implementation is critical in high-precision manufacturing environments [1].

A. Design & Prototyping

The first step in implementing the new solution was designing a custom assembly machine

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capable of performing the hole-making operation with high precision. This involved close collaboration with the automation company to translate the functional requirements into a detailed machine design. The exact hole dimensions, tolerances, and positions needed for wire passages were specified, along with considerations for part alignment and secure clamping to prevent any movement during operation. As noted by Li and Roberts (2017), tailoring machine design to specific manufacturing requirements is essential for achieving consistent precision and reliability [5].

To ensure operational safety and avoid unintended drilling cycles, light-curtains were integrated into the machine design as a fail-safe mechanism. These light-curtains were programmed to lock out the drilling operation unless the light beams remained uninterrupted. This provided an additional layer of security to ensure that the machine would only cycle under safe and proper conditions. Rolfes and Buchanan (2018) highlighted the critical role of light-curtain systems in safeguarding operators and equipment in automated manufacturing environments [7].

To stabilize the part during drilling, hydraulic-actuated clamps were installed as part of the machine design. These clamps ensured the part remained securely positioned throughout the drilling cycle, eliminating the risk of misalignment or vibration during the operation. Toyo and Tanaka (2019) emphasized the importance of robust part-holding systems in maintaining accuracy and precision in secondary operations [6].

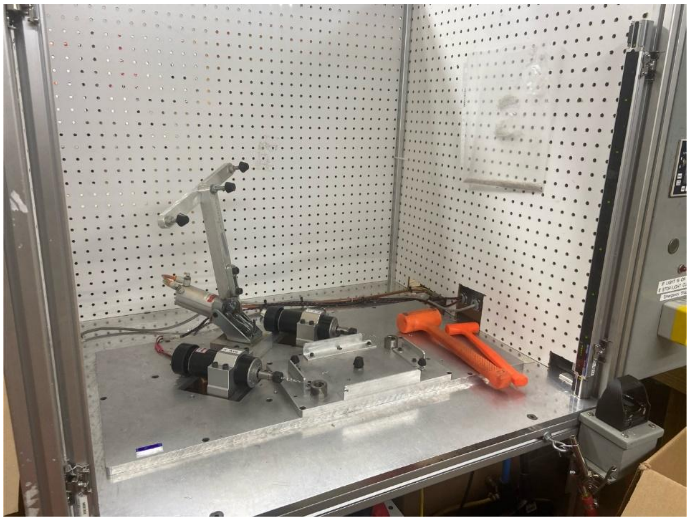

Figure 2: Detailed view of hole-making fixtures and clamp used in the assembly machine to hold the part securely.

The design phase concluded with the creation of a prototype machine, which was used to conduct initial tests and refine the system further. The combination of light-curtains for safety and hydraulic clamps for part stabilization demonstrated the reliability and practicality of the new design during prototyping.

B. Validation & Testing

With the prototype machine completed, the next phase involved rigorous validation and testing to ensure its performance met the required specifications and could withstand continuous production

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conditions. Validation included monitoring critical parameters such as hole size accuracy, positional tolerances, and cycle time. Liao and Wu (2020) emphasized that thorough validation under real-world conditions is essential to identify and resolve any operational inefficiencies before full-scale deployment [9].

Particular attention was given to testing the light-curtain system to verify its effectiveness as a safety mechanism. The system reliably locked out the drilling cycle whenever the light beams were obstructed, ensuring that operations were conducted under safe conditions. Additionally, the hydraulic clamps were tested to confirm their ability to hold parts securely without introducing deformation or misalignment.

C. Process Optimization & Efficiency Tuning

After validating the machine's functionality, the focus shifted to optimizing the process for maximum efficiency. Parameters such as drilling speed, feed rate, and cycle time were fine-tuned to ensure optimal performance without compromising quality. Time studies were conducted to balance speed with precision, reducing cycle times while maintaining consistent results. Zhang and Miller (2020) emphasized the importance of process optimization in automated systems to achieve both efficiency and reliability [3].

The inclusion of light-curtains contributed to safety and operational consistency, while the hydraulic clamps ensured positional accuracy, minimizing the risk of defects. The process optimization stage enabled the machine to operate seamlessly as part of the overall production line.

D. Quality Assurance Integration

A post-drilling quality assurance system was integrated to verify each hole's dimensions, depth, and positioning after the operation. This step ensured that any deviations were identified and corrected before the parts moved further along the production line. While no alignment confirmation sensors were present before drilling, the quality assurance process provided a robust mechanism for ensuring final product quality. Rolfes and Buchanan (2018) stressed the importance of embedding verification systems within automated processes to maintain high production standards [7].

E. Training & Operational Rollout

The final step involved training production staff to operate and maintain the assembly machine. Operators were trained on handling the light-curtain safety system and using the hydraulic clamps for secure part positioning. Training sessions covered troubleshooting procedures, error identification, and maintenance tasks to ensure the machine operated smoothly. Gu and Yan (2019) emphasized that proper training is essential to maximize the effectiveness of new manufacturing technologies [1].

The implementation process for the secondary hole-making assembly machine was a comprehensive effort involving meticulous design, rigorous testing, and detailed optimization. By integrating automation, sensor technology, and quality assurance measures, the machine successfully addressed the challenges of the previous process and delivered a reliable, scalable solution. As noted by Rolfes and Buchanan (2018), such transformative implementations not only resolve immediate technical challenges but also lay the foundation for long-term operational

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excellence [7].

VII. LIMITATIONS/CHALLENGES

Despite the success of the secondary assembly machine in addressing the issue of pin breakage, several limitations and challenges were encountered during the project. These insights provide valuable considerations for improving similar systems in the future.

1. Technical Complexity

The integration of light-curtains and hydraulic-actuated clamps added complexity to the machine's design. Ensuring seamless functionality of these components required significant engineering effort and customization. Gu and Yan (2019) highlighted that increased technical complexity in automation systems often extends development timelines and resource requirements [1].

2. Cost Implications

The initial investment for the development and integration of the assembly machine, including the light-curtains and hydraulic clamps, was substantial. Zhang and Miller (2020) noted that high upfront costs remain a challenge when implementing customized automation solutions, despite long-term operational benefits [3].

3. Manual Setup for Alignment

Although the hydraulic clamps stabilized the parts during drilling, the absence of alignment confirmation sensors meant that precise part positioning relied on manual setup. This dependency introduced additional operator effort and occasional production delays. Rolfes and Buchanan (2018) noted that manual setup requirements can reduce the overall efficiency of automated systems in precision applications [7].

4. Downtime During Implementation

Transitioning to the secondary hole-making process required halting production temporarily. Careful planning was necessary to minimize disruptions, but the downtime added short-term challenges to delivery timelines. Toyo and Tanaka (2019) emphasized that temporary downtime during automation implementation is often an unavoidable trade-off for long-term gains [6].

5. Scalability Concerns

The machine was specifically designed for the current part's dimensions and requirements. Any future design changes may necessitate further modifications to the machine, potentially limiting its scalability. Li and Roberts (2017) observed that while custom machines excel in precision, they can face challenges in adapting to evolving production needs [5].

6. Operator Training

The new system required operators to be proficient in managing the light-curtains and hydraulic clamps. Ensuring that production staff understood the safety protocols and maintenance procedures required significant time and effort. Gu and Yan (2019) highlighted the importance of comprehensive operator training in the successful adoption of new manufacturing technologies [1].

While the secondary assembly machine successfully addressed the pin breakage issue, challenges such as manual alignment setup, scalability concerns, and high initial costs remain important considerations. The integration of light-curtains and hydraulic clamps provided a reliable and safe solution but introduced complexities that must be managed in future implementations. Continuous improvement efforts will focus on addressing these limitations to further enhance system efficiency and adaptability.

VIII. CONCLUSION

The implementation of a dedicated secondary hole-making assembly machine has successfully resolved the recurring issue of pin breakage in the plastic injection molding process. By eliminating the need for mold-integrated pins and transitioning to a post-molding operation, the solution addressed the root cause of mechanical failures and significantly enhanced production reliability. The incorporation of light-curtains as a safety mechanism and hydraulic-actuated clamps for part stabilization ensured that the drilling operation was both precise and error-free. As Rolfes and Buchanan (2018) highlighted, the integration of fail-safe systems and robust part-holding mechanisms in automation is essential for achieving high manufacturing reliability [7].

The transition to this secondary operation has also delivered broader operational benefits. The removal of retractable pins simplified the mold design, reducing maintenance costs and extending the mold's lifespan. Additionally, the dedicated assembly machine offers the flexibility to accommodate future adjustments to hole specifications, ensuring scalability and adaptability. Toyo and Tanaka (2019) emphasized that such adaptable solutions are vital for manufacturers striving to meet evolving customer requirements [6].

From a financial perspective, the reduction in unplanned downtime and costly mold repairs has resulted in long-term savings. Zhang and Miller (2020) observed that automated systems equipped with fail-safes and quality control mechanisms can significantly improve operational efficiency and reduce waste [3]. Furthermore, customer satisfaction has been reinforced through collaborative validation and consistent delivery of high-quality parts, strengthening trust and positioning the company as a proactive and reliable manufacturing partner.

This project demonstrates the importance of innovation, collaboration, and systematic problem-solving in addressing complex manufacturing challenges. By integrating advanced automation technologies such as light-curtains and robust clamping systems, the company has set a new benchmark for operational excellence and quality assurance. Moving forward, this solution serves as a model for improving other manufacturing processes, ensuring scalability, safety, and efficiency in future operations.

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