THE EFFICIENCY COEFFICIENTS ANALYSIS (OEE) IN ALUMINUM CASTING PROCESSES: COMPARISON OF AUTOMATED AND SEMI-AUTOMATED SYSTEMS

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Abstract

This study explores aluminum casting processes' efficiency, focusing on comparing automated and semi-automated systems. Key factors such as productivity, quality, cost, and flexibility are examined to highlight the strengths and limitations of each approach. Automated processes generally offer higher efficiency due to their ability to operate continuously, ensuring better product consistency and reduced variability. In contrast, while initially more affordable, semi-automated systems may result in higher operational costs over time and require more human involvement, increasing the likelihood of errors. The decision to use automation or semi-automation largely depends on production needs: semi-automation is more suitable for small-batch production with frequent product changes, while full automation is more cost-effective for large-scale production with stringent quality control. Other factors, such as production cycle time, material consumption, machine downtime, and environmental impact, are also critical when assessing these processes. Additionally, the Overall Equipment Effectiveness (OEE) metric is employed to evaluate the efficiency of both automated and semi-automated processes, identifying potential areas for improvement in terms of availability, performance, and quality. This analysis provides valuable insights into optimizing aluminum casting processes to enhance production efficiency, reduce costs, and ensure high-quality output in the foundry industry.

Keywords: OEE coefficient, automated process, semi-automated process, aluminum casting, foundry industry

1. INTRODUCTION

Casting is one of the oldest and most versatile manufacturing technologies, with archaeological evidence indicating its use for over 7,000 years. In contemporary industrial settings, the process involves pouring molten material, typically a metal such as aluminum, into a mold shaped to replicate the desired component. After the molten metal solidifies, the cast is removed, completing the process. Aluminum casting has become increasingly important due to aluminum's low melting point, excellent castability, and ability to reproduce geometrically complex parts with high dimensional precision and minimal post-processing. Aluminum castings are essential in a wide range of industries, including automotive, aerospace, electronics, and telecommunications. These sectors value aluminum's low density, corrosion resistance, and thermal and electrical conductivity. Depending on the production volume, component geometry, and mechanical performance requirements, various casting methods are employed, including sand casting, die casting (high- and low-pressure), permanent mold casting, investment casting, and centrifugal casting [1]. Among them, high-pressure die casting (HPDC) is particularly well-suited to the mass production of small-to-medium-sized parts with thin walls and high surface quality.

Obtaining high-quality castings [2] is inextricably linked to diagnostic procedures of materials engineering [3], including image analysis [4]. This is essential in the case of implants [5], and especially in the case of biocomposites [6-8]. The precision and quality of castings also justify the use of this technology, which has high energy requirements [9,10], and the costs of this energy are becoming high in the context of a sustainable economy [11,12].

1.1 Aluminum casting alloys - chemical composition, casting technologies

Aluminum casting alloys are specifically engineered to optimize properties such as strength, fluidity, thermal conductivity, and corrosion resistance. These alloys are categorized based on their principal alloying elements [13,14]:

- Series: High-purity aluminum (≥99%) used in applications where corrosion resistance is critical but mechanical demands are low. Series (Al-Cu): Alloys containing copper, known for their high strength and thermal resistance.
- Series (Al-Si-Cu/Mg): Among the most widely used alloys due to excellent castability, moderate strength, and corrosion resistance (e.g., A356.0, 319.0, 380.0).
- Series (Al-Si): High-silicon content alloys that enhance fluidity for thin-walled and intricate parts.
- Series (Al-Mg): Magnesium improves corrosion resistance and weldability; these alloys are commonly used in marine environments.
- Series (Al-Zn): Zinc-based systems offering high strength, are used in critical structural components.

The equipment used in aluminum casting depends on the chosen technique and the application requirements. Cold-chamber die casting machines are commonly used for high-melting-point metals like aluminum, where molten metal is ladled into a chamber and injected into the die under high pressure, ideal for large-scale production. Sand casting offers flexibility, ranging from manual to fully automated lines, and is well-suited for large or complex shapes in small to medium volumes [15,16]. Permanent mold casting uses reusable metallic molds, offering better dimensional accuracy and surface finish than sand casting. Investment casting relies on expendable ceramic molds formed around wax patterns, allowing for high-precision parts. Centrifugal casting uses rotating molds to distribute metal evenly, enhancing density and structural integrity in cylindrical components. Modern foundries increasingly adopt automation technologies, robotic pouring, PLCs, and vision systems to improve consistency, reduce cycle time, and enable real-time quality control, contributing to greater process reliability and efficiency [16].

1.2 Aluminum casting processes engineering

The aluminum casting process involves several critical temperature parameters that directly influence the quality and performance of the final component. Pure aluminum melts at approximately 660°C, while casting alloys, depending on their chemical composition, typically melt in the range of 620°C to 750°C. To ensure sufficient fluidity for complete mold filling, the pouring temperature is usually maintained between 700°C and 750°C. In die casting, the mold or die temperature must be controlled between 180°C and 300°C to prevent premature solidification of the molten metal and to minimize thermal fatigue of the tooling. An essential aspect of the casting process is the precise control of thermal gradients during solidification. Improper cooling can lead to internal stresses, porosity, and hot tearing, defects that compromise both the structural integrity and surface quality of the cast part [17]. The cooling rate, which is determined by the specific casting method used, has a significant impact on grain size and mechanical strength. Because of the complexity, precision requirements, and high sensitivity to process conditions such as temperature control, cooling rate, and solidification dynamics, aluminum casting, particularly in high-integrity applications, is classified as a special process. According to quality management systems such as ISO 9001 and IATF 16949, a special process is one where the final product quality cannot be fully verified through subsequent inspection and must instead be ensured through controlled process parameters and qualified procedures. In aluminum casting, internal defects like shrinkage cavities, porosity, and microstructural inconsistencies often cannot be detected by visual inspection alone and may only be identified through advanced non-destructive testing. For this reason, strict process control, operator qualification, and equipment validation are essential to guarantee consistent, defectfree production, justifying its categorization as a special process within industrial manufacturing standards [18]. Recent advancements in aluminum casting are driven by digitalization, automation, and environmental sustainability. The integration of Industry 4.0 technologies, such as IoT-based sensors, AI-driven process control, and machine learning algorithms, enables predictive maintenance, adaptive casting parameter optimization, and real-time defect detection. For example, digital twins of the casting process are now being used to simulate thermal and flow behavior, improving first-pass yield and reducing scrap. Sustainability is also shaping the future of aluminum casting. Foundries are increasingly adopting closed-loop recycling, using remelted scrap aluminum, and integrating low-carbon alloys to reduce environmental impact. Energy-efficient electric furnaces and regenerative burners have replaced traditional fossil-fueled systems in many operations, aligning with global decarbonization goals [17,19,20]. In parallel with technological developments, foundries are assessing the operational efficiency of fully automated versus semi-automated casting lines. While semi-automated processes provide flexibility and lower capital investment, they are labor-intensive and prone to human error. In contrast, fully automated lines (equipped with robotics, CNC systems, and real-time quality control) offer higher precision, throughput, and consistency, though at higher initial costs and reduced adaptability for small-batch production. This study presents a comparative evaluation of two aluminum casting lines operating in the same foundry: one semi-automated and the other fully automated. Both lines produce identical components under the same quality requirements. The objective is to assess key performance indicators, such as cycle time, defect rates, energy consumption, and labor efficiency, in order to determine the impact of automation on process performance and product quality. The findings aim to support data-driven decisions in optimizing casting operations under contemporary technological and economic constraints.

2. EXPERIMENTAL

The OEE (Overall Equipment Effectiveness) indicator is a tool for evaluating the efficiency of machine and equipment utilization in production processes [21]. OEE measures how effectively production resources are used, taking into account three key factors: availability, performance, and quality. The OEE indicator is calculated based on three main components:

- Availability: Determines how often a machine is available for production compared to the planned production time, considering downtime due to breakdowns, repairs, or other disruptions.
- Performance: Measures how effectively a machine operates by comparing the actual production speed to the machine's maximum capacity.
- Quality: Measures the number of products that meet quality standards, accounting for scrap and defective products.

$$\text{OEE} = (\text{Availability}) \times (\text{Performance}) \times (\text{Quality}) \quad (1)$$

The OEE result is presented as a percentage, where 100% indicates full effectiveness (no downtime, optimal performance, and only products meeting quality standards). In the context of casting processes, the OEE indicator helps identify areas that require improvement in production processes, allowing for better management of time, costs, and product quality. In foundries, OEE can be used to assess the efficiency of both automated and semi-automated casting processes, highlighting inefficiencies such as downtime, low throughput, or quality issues that may affect the overall production outcome.

3. RESULTS AND DISCUSSION

The analysis of OEE (Overall Equipment Effectiveness) indicators in the context of semi-automated and automated aluminum casting processes aims to assess the efficiency of both production approaches. OEE is a measure that takes into account three key aspects: machine availability, performance, and production quality. The goal of this analysis is to compare both approaches based on OEE results, allowing for the evaluation of which solution is more suitable depending on production specifics, such as scale, type of castings, and quality requirements. The results of this analysis will aid in decisions regarding potential upgrades to production lines, ultimately contributing to process optimization and improved efficiency in aluminum casting production. The high-pressure die casting process for producing aluminum alloy components is carried out using a cooled, 10-cavity mold. Each individual part has an approximate mass of 460 grams. A single casting cycle lasts between 20 and 40 seconds, with the longer duration of 40 seconds adopted as the standard cycle time for production planning purposes.

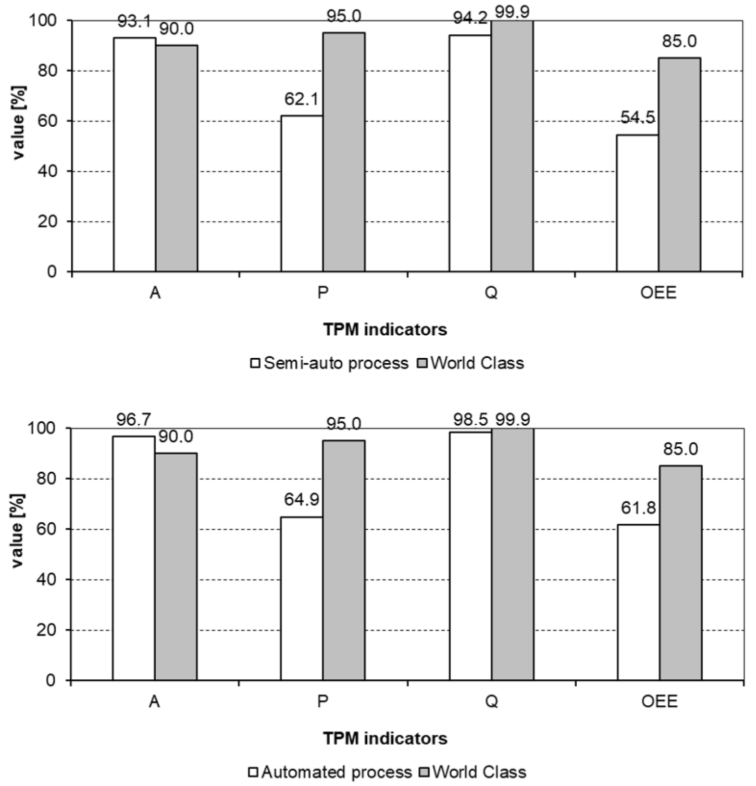

Figure 1 Overall Equipment Effectiveness (OEE) indicator and its components: a) semi-automated, b) automated aluminum die casting processes

Table 1 Analysis of high-pressure die casting process for aluminum alloy components

Category	Details
Mold Configuration / Part Weight	10-cavity / 460 g (0.46 kg)
Cycle Time / Cycles per Hour	40 seconds (standardized) / 90 cycles/hour
Cycles per Shift	720 cycles (8 hours × 90 cycles/hour)
Total Parts per Shift	7,200 parts (720 cycles × 10 cavities)
Gross Production Mass	3,312 kg (7,200 × 0.46 kg)

Based on this cycle time, the theoretical output for both the semi-automated and automated lines is approximately 7,200 parts per 8-hour shift, as detailed in **Table 1**. This calculation excludes downtime associated with scheduled breaks, as multiple operators work on a single machine, ensuring continuous operation on both lines. According to historical statistical data from the foundry, the average defect rate for these casting processes ranges from 5% to 10% for both production modes. Crucially, the target output, efficiency level, and acceptable defect rate remained consistent across both semi-automated and fully automated production modes during the study period, allowing for a direct and comparable assessment. The fact that both semi-automated and fully automated modes are held to the same production and scrap rate targets indicates a well-standardized process within the foundry. This also implies that, under current operational parameters, automation does not inherently offer significant efficiency gains in terms of theoretical output or targeted scrap reduction beyond the baseline achieved by the mature semi-automated production. Given the average defect rates between 5% and 10%, it is advisable to perform a detailed scrap cause analysis. This analysis should focus on factors like mold temperature stability, injection pressure consistency, alloy quality control, and the general equipment condition, as reducing these defects would significantly improve material efficiency and lower overall production costs. **Figure 1** presents the results for OEE indicator and its components, comparing the semi-automated (**Figure 1a**) and fully automated (**Figure 1b**) aluminum die casting processes. While the presented OEE values (61.8% for the automated process and 54.5% for the semi-automated process) provide a critical snapshot of current efficiency, it's essential to acknowledge the importance of OEE trends over time. A single OEE measurement indicates current performance, but longitudinal data are crucial for understanding the stability of the process, identifying recurring issues, and evaluating the long-term effectiveness of implemented improvements. For the scope of this comparative study, a detailed long-term trend analysis was not the primary focus, and the data represent a specific measurement period. However, the observed difference in OEE values between the two systems provides valuable insights into the immediate efficiency benefits of automation.

4. CONCLUSION

The comparison of Overall Equipment Effectiveness (OEE) values shows that the fully automated aluminum die casting process achieves a higher efficiency than the semi-automated process. Specifically, the OEE for the automated process is 61.8%, while the semi-automated process stands at 54.5%. This difference indicates that automation likely leads to more consistent equipment usage, fewer downtimes, and improved process stability. However, both OEE values are still below generally recognized industry best practices for high-pressure die casting (often cited around 80-85% for world-class manufacturing operations), suggesting room for further improvements in both processes. If feasible, shortening the cycle time from 40 to around 35 seconds could increase output by up to 15%, provided that quality and tool life are not negatively affected. Additionally, given the high volume of aluminum scrap, enhancing in-house recycling could significantly reduce raw material costs and improve sustainability. The automated aluminum casting process is characterized by greater consistency, higher efficiency, and lower operational costs in the long term due to fewer human errors and continuous machine operation. The semi-automated process, while offering greater flexibility and lower initial investment, is associated with higher operational costs and greater variability in quality. Although this study provides a valuable comparative snapshot of OEE values, future research should specifically focus on tracking OEE trends over extended periods for both automated and semi-automated lines. This will allow for a more robust assessment of the long-term sustainability of improvements, the impact of process changes, and the overall trajectory towards world-class manufacturing efficiency in the foundry.

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