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Analyzing Operation Management Methods for Defect Mitigation in the Mass Production of Green Car Parts

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Abstract. This research was conducted with the primary goal of investigating the root causes of defects in the mass production of green car parts and concurrently exploring the application of operational management principles within the domain of engineering economics. To achieve these objectives, a comprehensive methodology was employed, comprising cause and effect analysis, the Five Whys technique, and various quality control tools, such as P-charts, C-charts, X-bar charts, R-charts, process capability analysis, and acceptance sampling during sample production. The research adopted a dynamic approach, incorporating continuous monitoring, maintenance, and performance control in die casting and quality assurance during mass production. Lean production principles were also applied to ensure cost-efficiency, quality maintenance, and on-time delivery. Expert opinions, the Delphi technique, and economic outlook statistics were utilized to enhance the research. In conclusion, this study identified four critical factors essential for eliminating porosity defects in automotive die-casting mass production: gas-shrinkage solutions, mold design, material composition, and technological adjustments relating to atmospheric conditions. Operational management methods emerged as a promising approach not only in automotive die-casting but also across various industries, underscoring the continued significance of this research field.

Keywords: 5 Why's Analysis; Cause and Effect Analysis; Die-casting Mass Production; Porosity Defect; Quality Control Charts.

1. Introduction

Nowadays, internal combustion engine vehicles (ICEVs) still dominate the global automobile market, accounting for up to 76% of all vehicles, despite the increasing usage of electric vehicles (EVs) and hybrid vehicles (HVs). As global warming continues to be a pressing issue, there is a growing need for more environmentally friendly transportation options. However, EVs and HVs face limitations in driving range and higher purchasing prices, making them less accessible to the majority of consumers. In response, car manufacturers are seeking alternatives to make ICEVs more ecologically friendly. One effective method is the implementation of the Idling Stop System (ISS) technology, which temporarily shuts down the engine to save energy and reduce CO2 emissions when the vehicle is idle (Long, Huy and Van, 2022).

The mass production of die-casting green car parts is a critical process in the automotive industry. Unfortunately, this process often encounters defects that can compromise the quality of the parts, increase rejection rates, and result in customer dissatisfaction (Trang *et al.*, 2022). Defects can arise from various factors, including material composition, process parameters, equipment performance, and human error (Long *et al.*, 2023). Addressing the issue of defects in the mass production of die-casting green car parts is crucial for manufacturers to ensure product reliability, meet customer expectations, and remain competitive (Long *et al.*, 2019). By mitigating defects, manufacturers can improve overall part quality, reduce production costs, minimize scrap and rework, and enhance process efficiency.

To achieve defect-free production, effective operation management methods are essential. Analyzing and evaluating these methods can provide insights into their impact on defect occurrence and help identify strategies for defect mitigation (Le *et al.*, 2022). By implementing appropriate operation management techniques, manufacturers can streamline production processes, optimize quality control measures, and enhance the overall performance of the die-casting process.

Therefore, conducting research to analyze operation management methods for defect mitigation in the mass production of die-casting green car parts is vital. This research aims to contribute to understanding the key factors that contribute to defects, evaluating the effectiveness of different operation management methods, and proposing strategies to eliminate defects and improve the quality and efficiency of the manufacturing process.

2. Literature Review

The production of internal combustion engine vehicles involves over 20,000 parts, while hybrid vehicles require more than 8,000 parts from various manufacturers (Long, Khong and Tran, 2015). Ensuring attention to detail is crucial as manufacturers face challenges with rejected finished parts (Le *et al.*, 2023). Meeting the expectations for defect-free castings and timely delivery is a significant concern. Die casting is a cost-effective technique in the automotive industry, offering benefits like high-speed production, dimensional accuracy, and simplified assembly. However, manufacturers still struggle with rejected parts due to the attention to detail required and the demand for defect-free castings and punctual delivery (Long *et al.*, 2019).

2.1. Defect Classifications

Understanding the types and origins of defects in die casting is crucial before implementing elimination strategies. Defects in die casting can be classified based on their geometry or metallurgical origin (Gariboldi, Bonollo and Rosso, 2007). However, this classification system lacks an exploration of defects related to handling, finishing, and machining operations.

The classification system consists of multiple levels. At the first level, defects are categorized as internal, surface, or geometrical. At the second level, defects are further classified as shrinkage, thermal contraction, filling, metal/mold interaction, or phase-related defects. Existing research has introduced a simulation-supported approach to defect analysis, highlighting the limitations of process-focused methods (Mane, Sata and Khire, 2011). This approach follows a 3-step process based on defect appearance, size, location, consistency, discovery stage, and inspection method. It allows for grouping defects based on their effects on the casting, enabling symptom identification and cause determination. The process involves two phases: defect categorization and subdivision.

2.2. Fishbone Diagram

The Fishbone Diagram is a useful tool for identifying the main causes of a problem, including defects in the die-casting industry. Previous research identified shrinkage, porosity, and cracks as major causes of rejection in aluminum die-casting. However, the focus was on minimizing rather than eliminating defects. Similarly, a fishbone diagram was used to address crack defects in automobile and motorcycle parts die-casting, proposing countermeasures to reduce defects (Long *et al.*, 2019). In contrast, this research aims to eliminate porosity defects in aluminum die-casting, considering their impact on product performance. To overcome the limitations of the fishbone diagram, the study incorporates chemical aspects for a comprehensive approach to defect elimination.

2.3. Chemical Aspect

Previous research on aluminum die-casting defects has overlooked the impact of chemical components, focusing mainly on production aspects (Long *et al.*, 2019). This study aims to address this gap by considering the chemical aspects contributing to porosity defects in the die-casting process. Uneven chemical flow during the melting process of commonly used magnesium (Mg) and aluminum (Al) alloys can result in gaps and void spaces, leading to porosity defects and compromised mechanical performance (Tzamtzis *et al.*, 2009). To reduce the rejection rate caused by porosity, we propose addressing these chemical issues.

Researchers have suggested solutions to mitigate non-uniform chemical flow in aluminum die-casting. For example, adding Rhenium (Re) to the Mg-Zn-Al alloy reduces hot tearing susceptibility and potentially eliminates porosity-related defects by reducing pore formation. Similarly, adding Titanium (Ti) to Al-Mg-Si alloys improves mechanical performance and reduces hot tearing (MKTP, 2023).

However, none of the mentioned studies specifically targeted porosity defects, which have the second-highest rejection rate. To address this prevalent defect type, our research integrates the chemical aspects of die-casting to develop a solution that aims to eliminate porosity defects in the process.

3. Method

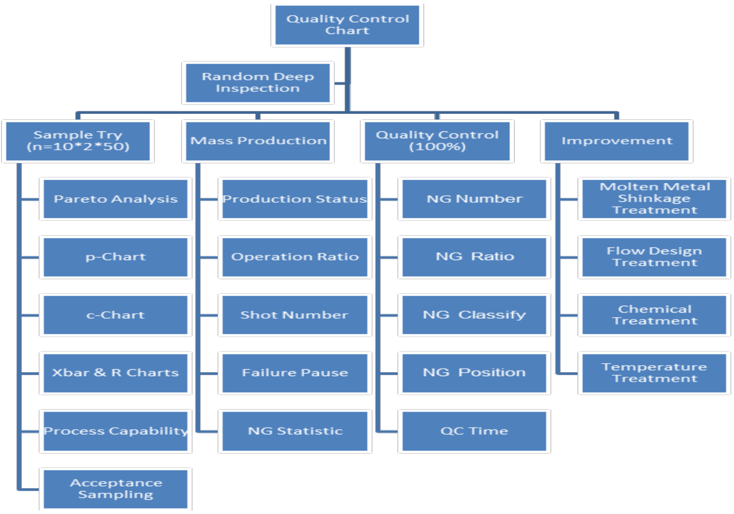


Fig. 1: Quality Control Chart

A quality control chart is designed in the work including cause & effect analysis; 5 why's analysis; Pareto analysis; quality control (P-chart, C-chart, Xbar & Range, Process capability, Acceptance sampling) for sample try production and pivot to monitor, maintain, control performance of die casting & quality control for mass production and apply lean production for maintain cost – quality – delivery; Expert opinions, Delphi technique and analysing the economic outlook statistics.

4. Results

4.1. Causes of Defects Analysis

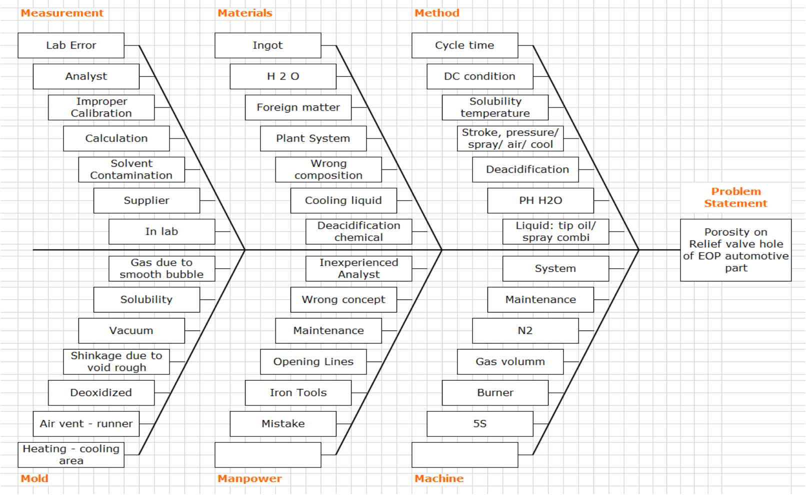


Fig. 2: Causes of Defects Analysis

4.2. 5-Why Analysis

To identify the possible roots of these causes, a 5-Why analysis is also applied to examine the elements which lead to the defects of porosity defects. The elements which are identified in the research including gas, gas bubles, metalic reactions and rough bubble voids. Figure 3 indicates the root causes of every single situation and its necesssary corrective actions and responsibilities.

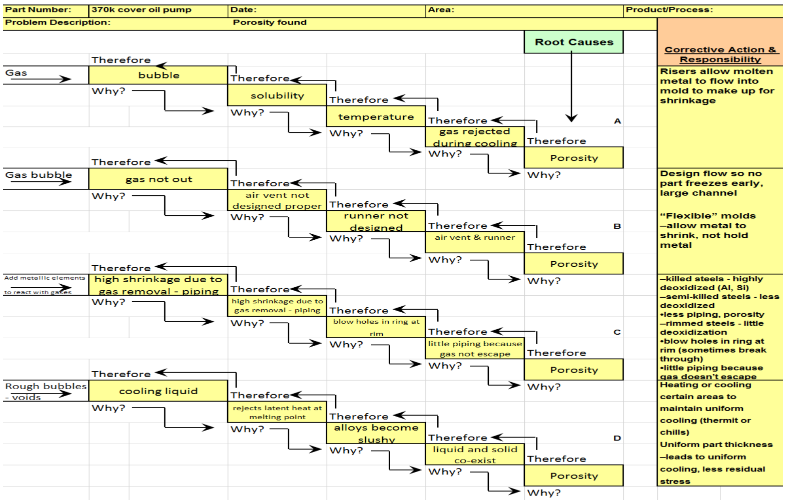


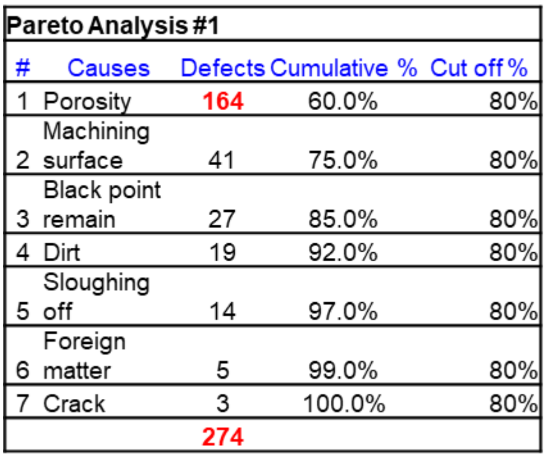
Fig. 3: 5-Why Analysis

4.3. Quality Control

Data of this research is collected and analysed based on 7 mold life from 100 to 1000 test pieces, about 800,000 pieces for mass production. To achieve this, try process with 10 molds model with 100 sample for each mold. The research is applied quality control including P-chart, C-chart, X-bar, R-chart, Process capability, Acceptance sampling for sample try production and pivot to monitor, maintain, control performance of die casting & quality control for mass production.

Try-process

Pareto Analysis statistical technique in decision-making is applied for the selection of a limited number of quality control tasks that produce significant overall effects. It uses the Pareto Principle (also known as the 80/20 rule) the idea that by doing 20% of the work you can generate 80% of the benefit of doing the entire job. The first cause covers 60% of the total defects. Porosity causes are considered Vital Few causes need to be priority controlled. Machining surface, black point remaining, dirt, sloughing off, foreign matter, crack causes… considered useful many causes.



Pareto Analysis #1

#	Causes	Defects	Cumulative %	Cut off %
1	Porosity	164	60.0%	80%
2	Machining surface	41	75.0%	80%
3	Black point remain	27	85.0%	80%
4	Dirt	19	92.0%	80%
5	Sloughing off	14	97.0%	80%
6	Foreign matter	5	99.0%	80%
7	Crack	3	100.0%	80%
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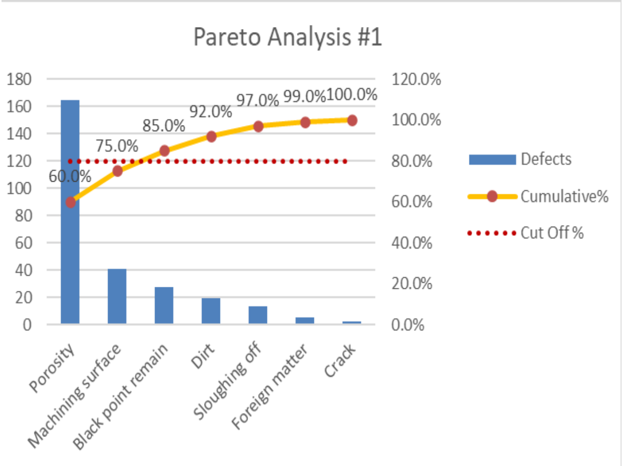


Fig. 4: Pareto Analysis

P-chart, C-chart, X-bar and R-chart

The p-chart, shown in Figure 5, is a tool used to monitor the proportion of defective items in a sample. It considers three main variables: the number of samples, sample size, and the number of defectives in each sample. The control limits on the chart, represented by sigma limits (Z-values), are typically set at 1, 2, or 3 standard deviations from the mean. The number of samples can range from 2 to 30, and there is no limit on the sample size. Excel is used to calculate the proportion of defectives (p-bar) and determine the control limits. The chart displays the control limits, a dotted line for the mean, and the proportion of defectives on the y-axis. A process is considered in control if all data points fall within the control limits without any noticeable patterns.

Similarly, the C-chart, depicted in Figure 5, is used to monitor the number of defects in a single item. It takes into account the number of samples, the number of defects in each sample, and the sigma limits, which are determined in the same manner as the p-chart. The number of samples can range from 2 to 30, and Excel is used for the calculations and to establish the control limits. The chart displays the upper and lower control limits, with the number of defects on the y-axis. A process is considered in control if all data points fall within the control limits and no patterns are observed.

The X-bar and R-charts, shown in Figures 5 respectively, are utilized to monitor the central tendency and dispersion of a process. The inputs include the number of samples, sample size, and data from multiple observations within each sample, ensuring a normal distribution. Excel is used to calculate the average of each sample for the X-bar chart and the range of each sample for the R-chart. The average of the averages, X-bar-bar, is also calculated and used in the control limit formulas. Both charts display the control limits, the mean, and X-bar/R-values. A process is considered in control if all data points fall within the control limits and no patterns are observed. It is important for both the X-bar and R-values to be within control for the process to be considered in control.

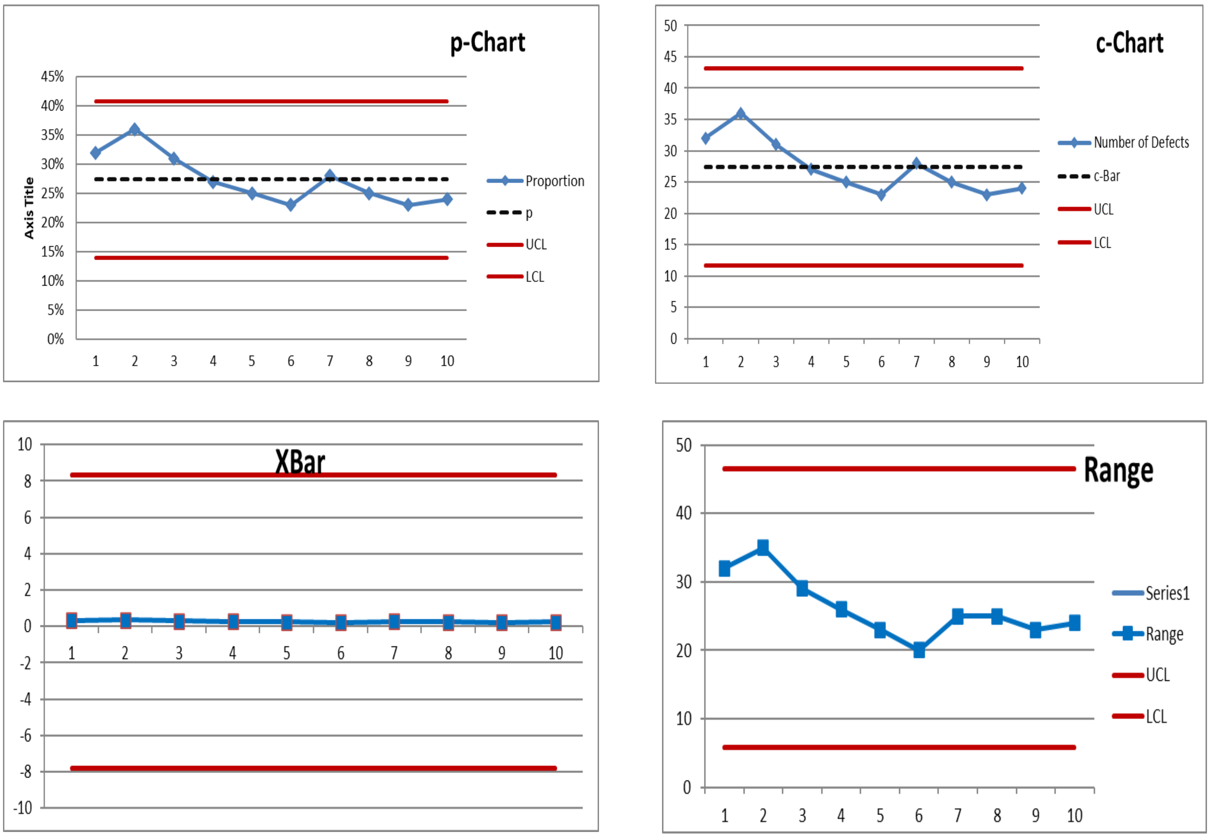
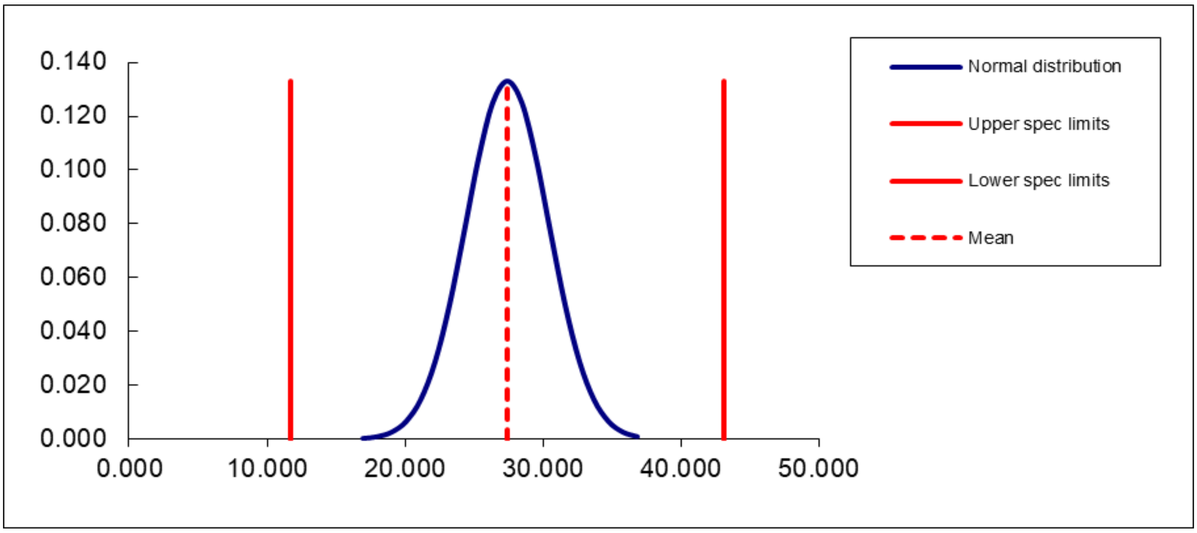


Fig. 5: P-chart, C-chart, X-bar and R-chart

Process Capability

In order to determine whether a process is capable of meeting product specifications, a process capability index is calculated to measure the capability of the process. The user inputs the design target, design tolerance, which is a +/- value expressed as a positive number, process mean and process standard deviation. Inputting these variables into Excel helps to calculate the upper and lower specification limits, as well as the process capability ratio and the process capability index, denoted as Cp and Cpk, respectively. The process capability ratio Cp is a ratio comparing the range of the design tolerance to that of the process. If Cp is equal to 1, the process is just adequate; if the process is less than 1, then the process is incapable; if the process is greater than 1, the process is capable. Noted that a Cp value of 1 is equivalent to 3 sigma quality, and it follows that a Cp value of 2 is equivalent to 6 sigma quality. Meanwhile, the process capability index Cpk determines whether the mean of the process is centered between the specification limits. This mean is considered to be centered when the process capability ratio is equal to its index. If Cpk is less than 1, the mean is off-centered and defects will occur; if Cpk is greater than 1, then the mean maybe off-centered but it is still capable of meeting product specifications. Noted that a process that is in control is not necessarily capable. Process capability determines whether a process is capable of meeting product specifications. The mean is centered when Cp and Cpk are equal. Process Distribution found the center, mean Cpk =1, the process is just capable.



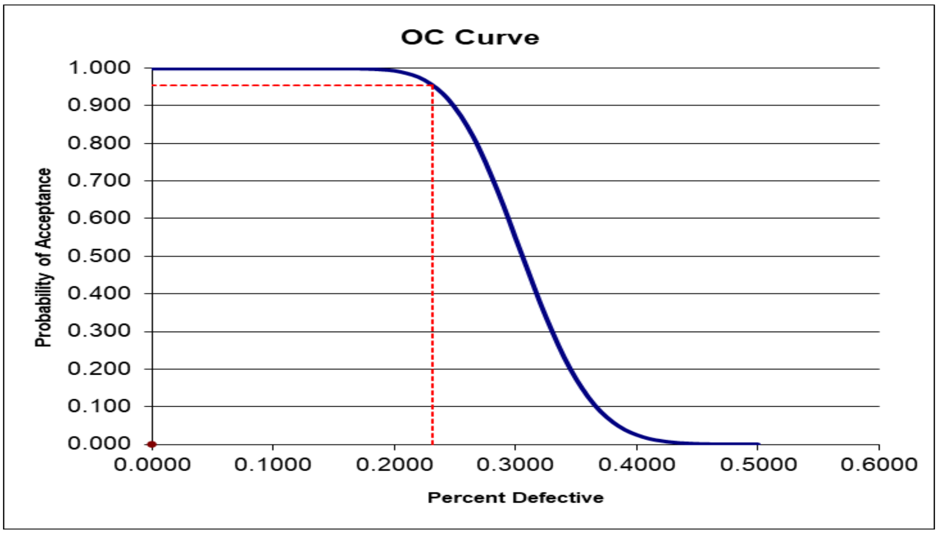


Fig. 6: Process Distribution and OC Curve

Acceptance Sampling

Acceptance sampling determines whether to accept goods based on sample results. Inputs like Acceptance Quality Level (AQL) and Lot Tolerance Percent Defective (LTPD) are used to calculate the sample size and acceptance number. AQL represents the acceptable percentage of defects, while LTPD is the maximum tolerated defect percentage. Calculations yield the sample size (number of items tested) and acceptance number (maximum allowed defects). Alpha denotes the producer's risk (probability of rejecting a good lot), and Beta denotes the consumer's risk (probability of accepting a bad lot).

A sampling plan is graphed by entering a sample size and acceptance number into the trial sampling plan. The best sampling plan model assumes an alpha of 0.05 and a beta of 0.10. An Operating Characteristics (OC) curve is constructed by inputting the sample size and acceptance number calculated earlier into the trial sampling plan, and this graph demonstrates the probability of accepting a lot given different levels of quality. Acceptance sampling is used to decide whether to accept a lot of goods based on sample results. To construct an OC curve for the best sampling plan, the actual Alpha=0.2320 and Beta=0.9549 be close to .05 and .10 meaning that the sample is accepted.

Mass Production

Alongside the Try-process model, the study applies Pivot in the mass production process in order to monitor, maintain, and control the performance of diecasting as well as quality control. The improvement process is done in the end by repeating the Try process and choosing the best model to apply for mass production.

Since the entire diecasting production process is applied to a mass production scheme, it is necessary to determine the most common defects. This can be done by improving the diecasting process and quality control. Quality control can help identify the defect errors that occur the most, and from there improving design change in mold can help prevent the defects from reoccurring. As the mold life is only capable of producing 200,000 shots at its maximum capacity, whenever the mold produces worse quality products, the Try-process is employed to put the old mold through a design improvement process. This trial process is repeated until maximum efficiency can be reached. The research account for the cost of the new mold is $480,000, and the cost of each improvement design change is $50,000; the maintenance fee, as well as mold-related parts, are also accounted for, as $250,000 each.

Improvement Result

The OC curve indicates the probability of acceptance to be close to 0.95 and the percent defective to be close to 0.9, which is similar to the projected values of Alpha and Beta stated above. After several design changes with the outflow, some noticeable improvements are observed. Specifically, the mold fee per part has been reduced to $6.5 to $3.9 per part, and the production fee to $1.8 per part. Furthermore, the percent defectives caused by porosity has been reduced to approximately 7% from 24%.

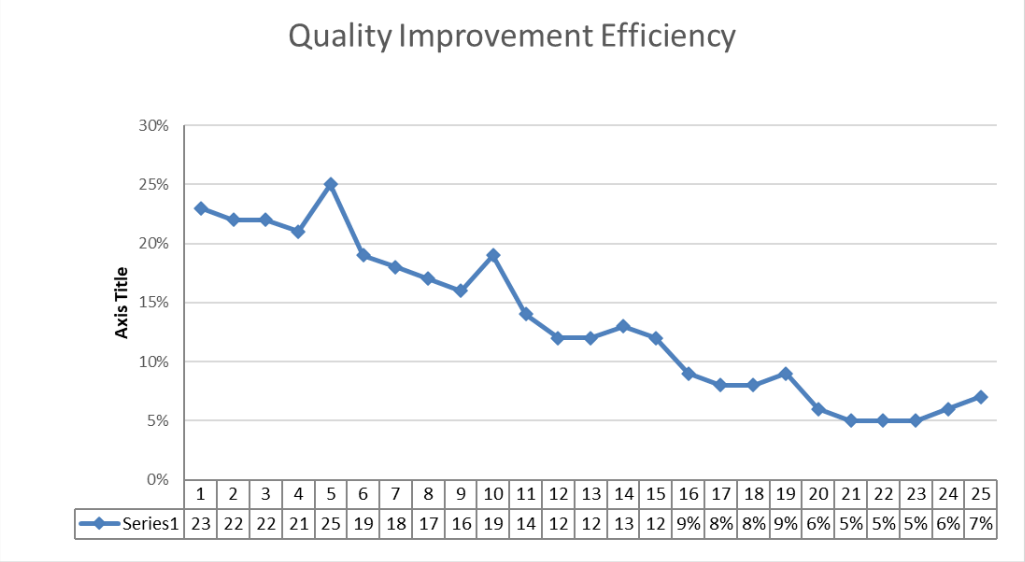


Fig. 7: Improvement Efficiency

5. Conclusions

5.1. Practical Implication

By implementing these improvements, several quality objectives can be achieved. The first objective is risk control, which involves monitoring performance changes, identifying new defects, addressing repeated defects, and monitoring material and equipment settings. By identifying abnormal characteristics and implementing countermeasures, the risks associated with defects can be minimized.

Defect analysis is essential to ensure proper functioning of the process. Production records and inspection results should be documented within 5 hours. Defective products should be investigated and confirmed within 1 day, and a report analyzing the cause of failure should be submitted within the following week. Temporary corrective action should be taken within 3 days of identifying a defect, with permanent corrective action implemented as soon as possible. In cases where defective products have been delivered to customers, preventing further distribution is crucial, and customer feedback should be sought to analyze the causes and find solutions for the defects.

Traceability of defective parts is another important objective, allowing for efficient identification and estimation of the volume of defective products. Each product should be marked with identification information such as lot numbers or assembly dates. This enables prompt countermeasures to be taken.

Controlling supplier quality is another objective that improves the overall quality of final products. It involves a thorough inspection of materials upon receipt, enhancing traceability between product lots and materials used, and managing the supply capacity of materials. Standardizing these processes helps ensure consistent quality and quantity of products.

Ongoing staff training is crucial to ensure the quality of processes. Since most procedures are performed by humans, well-trained operators are essential. Instruction manuals should be available, risk control procedures should be established, and regular training sessions should be organized to familiarize operators with materials and procedures.

Lot failure prevention is another significant objective. Any abnormalities observed during the production process should be immediately reported to management. Rather than implementing immediate fixes, the focus should be on investigating the causes and finding appropriate solutions. Design reviews should be conducted whenever changes occur, considering potential side effects.

By incorporating these seven quality objectives, along with the Try-process, defects in products can be effectively prevented.

5.2. Recommendations and Conclusions

The research's aim is to determine the root causes and to propose solutions and preventions that can minimize the defects that exist in aluminum diecasting products. As these diecasting products are parts of the ISS system for ICEV, it is essential that the safety measure of these products is accounted for, since any small defect in a product can have detrimental consequences. Furthermore, since these diecasting parts are being mass-produced, there is also the risk of the defects being mass-produced and delivered to consumers as well, so prevention methods are needed.

The research has found that development in operation management is the appropriate approach to eliminate defects in aluminum die-casting products. After making several attempts to alter the mold design with changes in the outflow, the research has found that the change has reduced the rate of defects from 24% to 7%. Asides from making changes to the mold design, it is necessary to control the quality of products by having ongoing training for staff and operators, so that the quality of the monitoring and maintenance process can be ensured as staff have familiarized themselves with the procedures. From this research, further research can be done by looking at other mass production products other than vehicles, such as motorcycles, to see how those products differ from the ones studied in this research. Moreover, manufacturers can utilize this research by implementing the operation management method so that manufacturers will be inclined to enforce prevention methods and approaches to handle a defect when an abnormality arises during production.

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