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CAUSES OF DEFECTS IN GRAVITY FLOW DIE CASTING PROCESS: INDUSTRIAL CASE STUDY

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Abstract

This study focuses on casting process parameters that affect the quality of automobile products. The objective of this study is to conduct a thorough examination of the gravity flow die-casting process and to identify the sources of defects in the braking bracket component. Systematic literature and practical study of the gravity flow die-casting process to identify the process parameter for which many defects occurred in the component. The Pareto chart is to be used to find out the most common casting defects reflected in the casting process and the cause and effect (Ishikawa) diagram is to the identification of the most significant factors that causes the defect in the casting. In the braking bracket shrinkage occurred due to the high pouring temperature and short solidification time. With the presence of oxides and hydrogen gases and the inaccurate position of venting in the die, a blowhole occurred. Insufficient volume of molten metal and complex design of getting system unfilling occurred. Due to high or low die temperature and internal thermal stress concentration cracks occurred on the casting surface. In today's competitive world, casting industries face challenges identifying defects and manufacturing defect-free castings. This industrial case study provides in-depth knowledge of casting defects and their root causes of shrinkage, blowholes, unfilling, and crack defects. This study helps to industry to improve product quality.

Keywords: casting, Ishikawa diagram, Pareto chart, pouring temperature, casting simulation

1. INTRODUCTION

Metal casting is the most significant process in mechanical engineering for manufacturing a complex geometrical shape and size of a component with high dimensional accuracy. Such complex shapes and sizes of components are used in various sectors like automobile, aerospace, marine, agriculture, railways, electrical, earthmoving, sanitary, industrial machines, etc. In the metal casting process complex shape mold cavity is made up of metal or sand and pouring the liquid phase molten metal in a cavity and solidified to obtain desired shape cast component (Campbell J., 2015; Ravi B., 2005). A metal casting process involves many steps to cast a complex shape component such as component geometry, design method, die and pattern making, pouring, fettling, heat treatment, shot blasting, and inspection. Figure 1 represents the various steps involved in manufacturing a complex geometrical shape cast component (Khan MAA., et al., 2017). Manufacturing such complex geometrical shape and size components are most challenging task available in traditional machining processes. Due to that reason, most industries strongly recommend the casting process (Kirkwood D. H., 1994; Fan Z., 2002). The casting process can manufacture such complex shaped and sized components with high dimensional accuracy. These complex geometrical shape components are manufactured by using various modified and advanced casting processes. Figure 2 represents metal casting processes with a range of components, process times, and materials used in them. As per the Foundry Informatics Center and Statista Research Department, information the overall casting production Worldwide is 105.5 million metric tons, and in India is 11.31 million metric tons during 2020-21 (Statista Research Department). In Indian total of 4500 casting industries out of which 1500 casting industries have International Quality Accreditation (Foundry Informatics Centre).

Figure 1. Process of metal casting

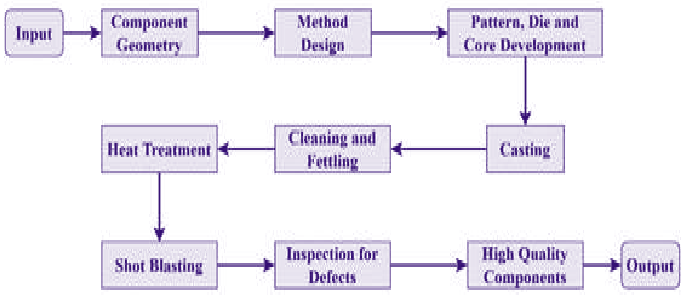
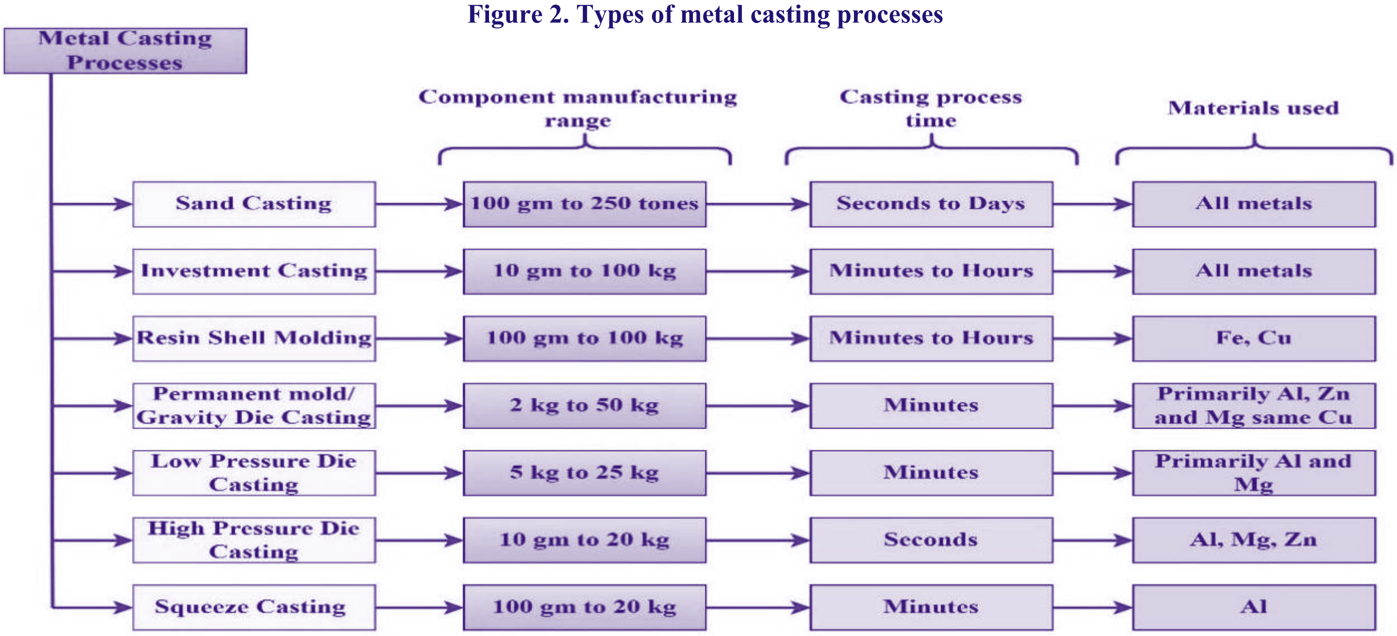


Figure 2. Types of metal casting processes



Nowadays, in the automobile, railway, marine, etc. industries there is an increasing demand for lightweight casting components to increase fuel efficiency performance, save petroleum fuel, and control CO2 emission. Due that so many steels, cast iron material components are replaced by Aluminium, Copper, Zinc, and Magnesium, and their alloys are the most common casting materials used. These materials have excellent mechanical properties are low density, light in weight, higher strength-to-density ratio, are non-magnetic, and have higher conductivity, and corrosion resistance. At present, many casting industries are facing numerous challenges to reduce casting defects, high casting yield, optimization of process parameters, increase mechanical properties, etc. There are many controlling factors involved in the casting process to manufacture a good quality product. During the casting process, many defects occur, which shows the poor-quality product. It demonstrates the significance of the casting process and, as a result, has become an area of attention in terms of finding the causes of defects, defect reduction, and process improvement. An industry located in Pune MIDC of the Maharashtra state is a leading manufacturer and supplier of braking system components for Three-Two-wheeler automobiles. The industry has established in the year 2012. They manufacture brake calipers, master cylinders, Tandem cylinders, brackets, etc. The industry uses a gravity die-casting process for the manufacturing of components. Presently the industry, facing the problem of a higher rejection of 35.50 % in automobile braking bracket components due to various casting defects like shrinkage, blowholes, unfilling, cracks, etc. Component rejection on the higher side reduces casting productivity and quality. It also has an impact on the industry's reputation. The objective of this paper is as follows:

- To review and study the significant process parameters affecting casting rejection through die-casting (Gravity) process.
- To identify the causes of defects in the braking bracket component.
- To recommend techniques for minimizing casting defects.

The present study consists of five sections which include the introduction, its importance, and research objectives in section 1. Section 2 of the article addresses the literature review and gaps identified from the previous research work. Section 3 represents the practical case study of the gravity flow die-casting process in the industry. In subsection, the Pareto chart is to be used to find out the most common casting defects reflected in the casting process and the cause and effect (Ishikawa) diagram to the identification of the most significant factors that cause the defect in the casting. Section 4 depicts the findings and discussion of the causes of defects in components. And the last section of the article constitutes the conclusion.

2. LITERATURE REVIEW

One of the authors explained the prominence of simulation in the casting process and its technical resources. He also highlights about using simulation software in casting industries the number of trials can be avoided in the production lines (Ravi B, 2008). Auto CAST simulation software was used to locate the shrinkage defect location in the component (Choudhari et al., 2014). After modifying the riser and getting the design of casting and simulation they observed minimum shrinkage in the gearbox component. Pro CAST simulation software was used to identify the location of shrinkage porosity defect in the gate runner (Zhang J., et al., 2014). A simulation was simulated using the pouring temperature of 750°C, and die temperature of 400°C. The simulation result shows very less shrinkage porosity defect in the gate runner of the casting. Several trials were conducted to simulate different feeding systems using AutoCAD simulation software (Bhatt H., et al., 2014). The simulation was simulated varying the dimension of the riser and location. At 200 mm riser diameter, and 230 mm riser height less shrinkage defect was observed as compared to the other dimension of it. The simulation was performed on LM25 and LM6 casting material components by using the Solid CAST simulation software (Hussainy S. F., et al., 2015). At 250°C die temperature, the LM25 material casting shows better performance. Modifying the riser design and again simulating in software the simulation shows no defect in casting at 35 mm riser diameter. MAGMA software was used to identify no shrinkage porosity defect (Patil R. T., et al., 2015). A simulation was performed using the process parameters, pouring temperature 730°C, die temperature 350°C, pouring time 7 sec, solidification time 200 sec, and molten metal velocity 1 m/s. The simulation results show shrinkage porosity defects in the casting components. The simulation analysis results in saving time and casting material to increase the productivity of the component (Nimbalkar V.V., et al., 2015). They used Auto CAST-X flow simulation software for the analysis. After modifying the gating system 10 % yield was observed in it. The comparative study of various simulation software referred the authors (Khan M A A and Shaikh A K, 2018). Their comparative studies were very helpful to many casting industries and researchers in the selection of simulation software.

By reviewing the various articles, it was observed that many researchers simulate their casting model geometry to diminish the shrinkage casting defect by selecting the pouring temperature, die temperature, pouring time, and molten metal flow rate or doing the modification in the getting and riser design. Such advanced tools help many industries or dynamic researchers to avoid physical trials on the shop floor and to save the cost and time of casing industries.

The die temperature casting process parameter has the most significant impact on casting defects, phase distribution, and grain size. Casting component mechanical properties were significantly affected by die temperature during the solidification process (Goenka M,. et al., 2020). On the other hand, it was observed that at very high die temperatures a coarse grain structure and serve casting defects were seen (Wang F., et al., 2017). They varying the die temperature from 140°C to 380°C the severity of crack (hot tearing) defect was observed in the AZ91D magnesium alloy (Bichler L., et al., 2008). They advised that for reducing the crack (hot tearing) casting defect to control the die temperature below 367.85°C to AZ19D magnesium alloy (Huang H., et al., 2017). By reducing the crack (hot tearing) defect in Al-Si-Cu alloy to maintain the appropriate die temperature for it. The size of the grain has a significant impact on the quality and mechanical properties of the casting components. Refine grain structures has excellent surface finishing and excellent mechanical properties (Rathi S K., et al., 2017). During the solidification process refine grain structure was obtained by using various techniques. The refinement of grain structure can be obtained by using various techniques like changing the chemical composition of an alloying element, adding some alloying element in material composition by the heat treatment process, and filling the cavity of desired shape with a different frequency of vibration.

In broad-spectrum, it was observed that aluminum alloy has excellent casting ability. From the review of various casting materials and techniques of refinement of grain structure, to manufacture a defect-free casting component proper die temperature should be maintained during solidification. Adding or changing the chemical composition of the casting material a refinement grain structure was formed in the casting which improves the surface quality and mechanical properties of the casting component.

They used the Taguchi experimentation method to check the process parameters like sand particle size, pouring temperature, cooling time, and pouring height, etc. we're affecting defects in the sand-casting process (Noorul H A., et al., 2009). Some authors performed the experimentation by selecting the 180°C die temperature and 250°C sleeve temperature and using the GISS process. It was observed that a uniform microstructure and a small amount of porosity were produced in the samples (Janudom S., et al., 2010). They conducted experimentation for thermal control on GDC by using the genetic algorithms approach. It was observed the left section was cool faster than the right section. So, by using the GA optimization algorithms uniform solidification was achieved (Dennis Wong M L and Pao W K S, 2011). To identify the casting defects and optimize the process parameters, the Design of Experiment (DoE) were utilized (Dabade U, Bhedasgaonkar R., 2013). They performed the analysis by using a Taguchi-based L18 orthogonal array to analyze the result of the S/N ratio in the first half. They also used ANOVA analysis to check the performances of casting yield on getting system process parameters (Pandit D., et al., 2019). They reported the influences of process parameters on the heat transfer coefficient using the statistical ANOVA methods. The experimental analysis was conducted at a pouring temperature of 720°C. During the experimentation cooling oil temperature was set to 30°C, 100°C, 200°C, and 300°C. Mold inserts were made of steel and copper materials. Cooling channel distances varied from 10 to 15 mm. At a cooling oil temperature of 100°C it was observed that copper mold material has the highest impact on the heat transfer coefficient (Wol N., et al., 2020). The use ofthe Six-Sigma DMAIC approach and Taguchi techniques for creating an L9 orthogonal array to diminish the defect in the external bearing ring (Omprakas M A., et al., 2021). By reviewing the various articles, it was observed that many researchers used numerical methods to optimize the process parameters along with experimentation or simulation to validate the result of its.

Many researchers used a root cause analysis analytical tool to identify the root of the defects and most contributing the factors of the casting. They used the Pareto chart analysis of rejection and find the cause of defects by using the Ishikawa diagram. They also suggest corrective remedies to improve the quality and productivity of the component (Joshi A, Jugulkar L M., 2014). They investigated the root reasons for casting defects in the engine parts (Ingale V and Sorte M., 2014). Plotting the Ishikawa diagram reveals the primary causes of shrinkage defects in automotive body casting. From this diagram, they observed that less amount of molten metal was poured into the riser due to which maximum components were rejected by shrinkage defect (Chokkalingam B., et al., 2017). They developed an integrated module to analyze the casting defects. It was a computer assistant interactive module for small and medium-scale foundry industries (Mehta N., et al., 2021). Performed the root cause analysis and applied the Six Sigma DMAIC method to reduce the defect in casting. They find out the causes of defects as human error, lack of communication, measuring error, checking, etc (Chelladurai C., et al., 2021). They conducted an industrial case study to identify the causes of defects in the cylinder block of automobiles engine manufactured by using a high-pressure die-casting process. In Pareto chart analysis they observed that 80% of rejections of components were due to various casting defects in the components (Bharambe C., et al., 2023). By reviewing the above articles, it was observed that many researchers used the Pareto chart analysis and root cause analysis to identify the targeted major contributed defects and their causes in the casting.

2.1 Research Gaps

By reviewing the various articles related to the casting processes, it was observed that many researchers adopted or suggested different methods to reduce casting defects. However, some research gaps were observed in it as follows:

- A specialized application like a braking system in an automobile was not analysed.
- Simulation and experimental analysis have been carried out to minimize a few casting defects (like shrinkage, and blowholes) only.
- In simulation analysis, human factors (Likes experience of the operator, Attention of the operator, etc.) were not considered.
- Experimental process validation for varying parameters was not analysed.
- Prediction of defects before the actual manufacturing was not observed.

3. CASE STUDY

One of the leading manufacturers and suppliers of aluminium gravity flow die-casting products for the two/three-wheeler brake systems industry of India located in Pune. The company is certified as per the technical specification standard IATF 16949:2016 and thus ensures the product quality of automotive components. In addition to the product quality standard, the company has also certified and established the Environmental Management System as per international standard ISO 14001:2015 and Occupational Health and Safety Management System as per international standard ISO 45001:2015.

The company has the skill & technical expertise to provide quality castings for complex applications across diverse industrial segments through specialized processes & cutting-edge technologies. Precision–engineered components & products satisfy the customer's needs & expectations in terms of quality & excellence. Presently, the industries facing a higher rejection (35.50%) in the automotive braking bracket component. These 35.50 % rejections were observed in twelve months. Such, a high rejection in components impact on the productivity as well as the quality of the product. The productivity and quality of the casting directly impact the reputation of the industries. This braking bracket component was used in a two-wheeler motorcycle (at a rare wheel). The die casting (gravity) - GDC process was used to manufacture the component. Die casting (gravity) process developed for manufacturing the complex geometrical shapes of automobile components. It has vertical mold openings and tilts between 0 to 90° angles with the tilting arrangement. The molten metal was poured directly into the mold opening and filled into the mold cavity using a tilting arrangement of die at a specific tilting angle.

3.1 Production of Braking Bracket

Figure 3 represents the die casting (Gravity) process flow chart. In identified casting industry an automobile braking bracket casting manufacturing process was observed and studied. An automobile brake bracket production process (raw material to dispatch of components), activities performed by production (process and behavior of operators), and quality (testing and inspection of components) departments are manually observed and noted. Stepwise process of production of the brake bracket is mentioned below:

- As per the customer's requirement, LM-16 aluminium alloy materials in ingot form were ordered by the purchasing department.
- The accepted ingot form material is separately stored with an 'OK' tagging label in a storage area.
- The accepted ingot transport through overhead care to the furnace for the melting process.
- A furnace fired by piped natural gas (PNG) is used to melt the ingot from raw materials. Keep the furnace temperature between 730 and 745°C. The Flux 11 faseco powder is used to remove dross and solid contaminants from molten metal. A sample of molten metal is taken from the furnace every 2 hours to check the chemical composition of the casting material.
- A density test on molten metal samples was performed to verify the presence of hydrogen and oxide.
- The die is clamped on the production line by a production team, and the operator preheats the die at 280 to 310°C.
- Using a scoop, the operator manually picks molten metal from the furnace and pours it into the die cavity. The molten metal enters the cavity with the help of a tilting arrangement.
- Following the solidification time, the operator removes the casting using the ejecting pins.
- Then excess part of the casting (getting and riser) was removed by using the machining process.

- The T6 heat treatment process was used to increase the strength of the casting.
- After that shot blasting process was performed to polish the surface of the casting.
- Finally, a one-to-one inspection of casting is done in the quality department. The accepted casting is finally dispatched to the customers.

The LM-16 aluminum alloy material was used to cast the component. Table I represents the chemical composition of LM-16 aluminium alloy. The details of the braking bracket casting process parameters are tabulated in Table II.

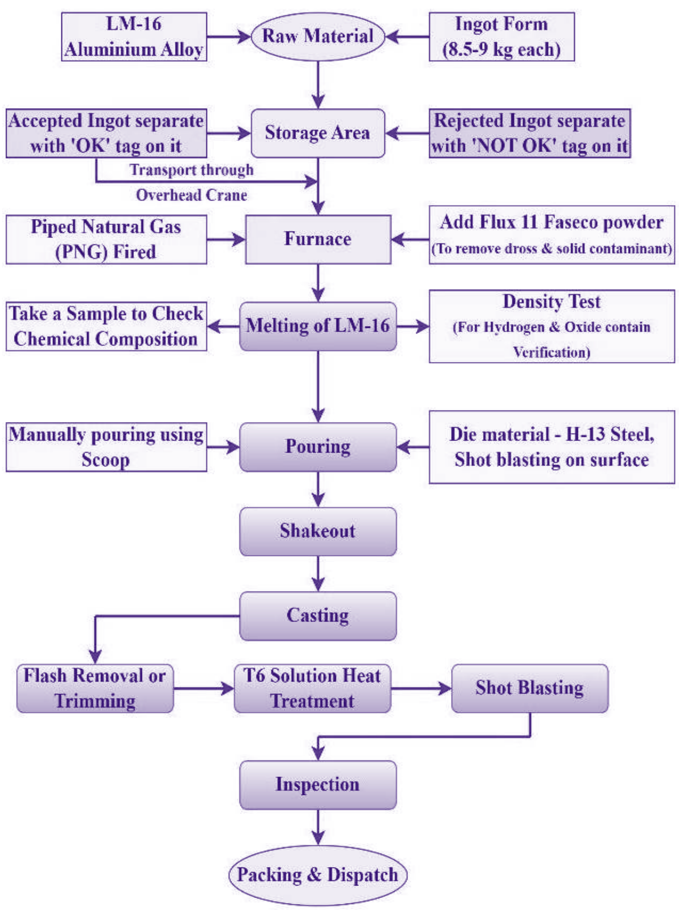


Figure 3. Die casting (Gravity) process flow chart.

To find the rejections in the castings, Twelve Months of rejection data were collected from the industry for analysis. Using that historical data contribution of the defect sheet was prepared which helps in identifying occurrence defects in automotive braking bracket casting. Overall 35.50 % of rejection of casting was observed. During this span total of 73413 castings were manufactured out of which 26064 castings were rejected due to various casting defects. The rejection data of casting was prepared, which described the quantity and percentage contribution of various defects. Table III represents the percentage of defective castings. Shrinkage (34.37%), blowhole (27.11%), unfilling (12.02%), rubbing (7.50%), die coat (7.07%), and crack (10.78%) are the major contributors to overall casting component rejection.

Table 1. Chemical composition (in %) of LM-16 Aluminium alloy

Si	Fe	Cu	Mn	Mg
4.50-5.50	0.0-0.6	1.0-1.5	0.0-0.5	0.4-0.6
Cr	**Ni**	**Zn**	**Ti**	**Al**
0.0-0.3	0.0-0.25	0.0-0.1	0.0-0.2	Bal.

Table 2. Braking bracket process parameters

Title	Details
Casting Material	LM-16
Casting Process	Die casting (Gravity) - GDC
Furnace Temperature (Molten metal)	730-745°C
Pouring Temperature	700-720°C
Die Temperature	280-310°C
Pouring Method	Manually
Pouring Time	5-7 sec
Tilting angle	90°
Tilting Time	7-9 sec
Number of Cavity in the die	Two
Solidification Time	115-150 sec

Table 3-Percentage of defective casting

Defects	Quantity of Rejection (Nos.)	Rejection Contribution (%)	Cumulative %
Shrinkage	8958	34.37	34.37
Blowhole	7066	27.11	61.48
Unfilling	3132	12.02	73.50
Rubbing	1954	7.50	81.00
Diecoat	1844	7.07	88.07
Crack	1417	5.77	93.84
Inclusion	576	2.21	96.05
Damage	439	1.68	97.73
Pinhole	263	1.01	98.74
Other	415	1.26	100

3.2 Pareto chart Analysis

A Pareto chart or diagram aids in the definition of the target. It also demonstrates that the most common casting defects are reflected in the casting process. It also displays the defect's contribution as well as the cumulative contribution of defects in terms of quantity and percentage as shown in figure 4. According to the Pareto chart of defects, the four types of defects, namely shrinkage, blowhole, unfilling, and crack, contribute 78.9% of rejection in castings, while the remaining types of defects contribute only 21.1% of rejection. Casting defect analysis will be performed for 78.9% of contributing rejection defects based on the above report. For that, root cause analysis and remedial actions are to be taken or carried out to minimize the casting defects for the improvement of the product quality. The present study is focused on finding the root causes of each defect by using a cause-effect (Ishikawa) diagram. Many metal casting industries follow brainstorming practices to find causes of defects in the casting. Figure 5 Pareto chart of casting defects represents the span of months in which casting has the maximum % of rejection in shrinkage, blowhole, unfilling, and crack.

Figure 4. Pareto chart of braking bracket

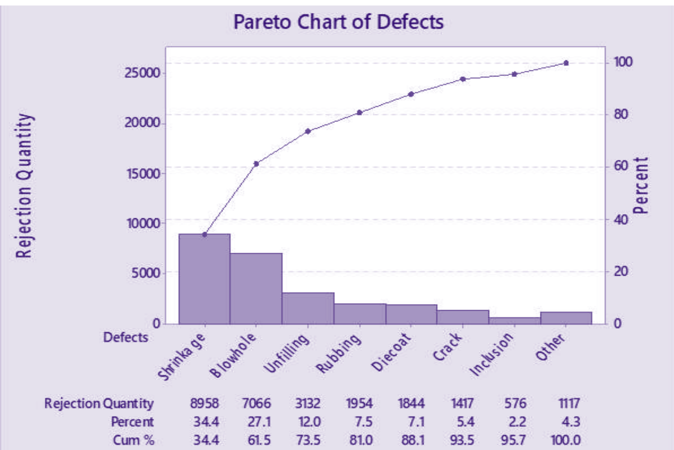


Figure 5 (a)-Pareto charts of Shrinkage

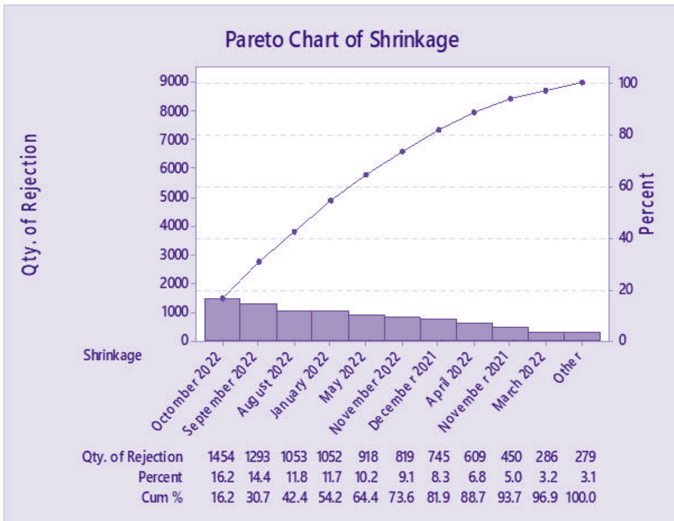


Figure 5 (b)-Pareto charts of Blowhole

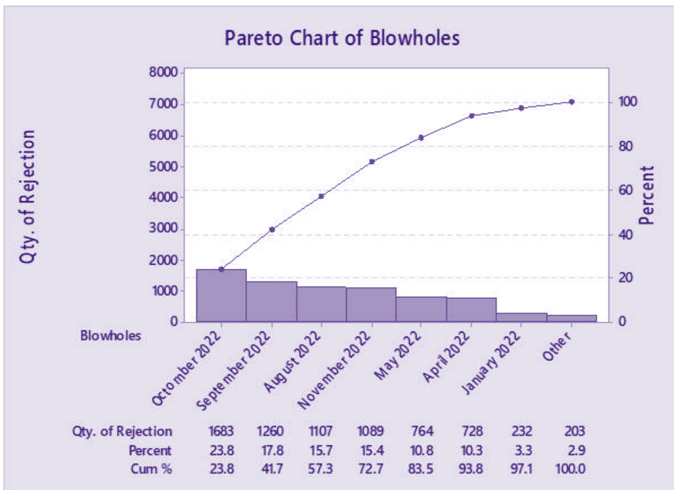


Figure 5 (c)-Pareto charts of Unfilling

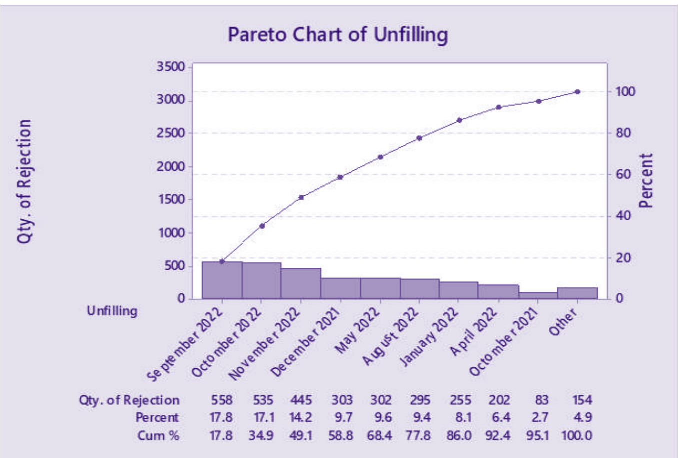
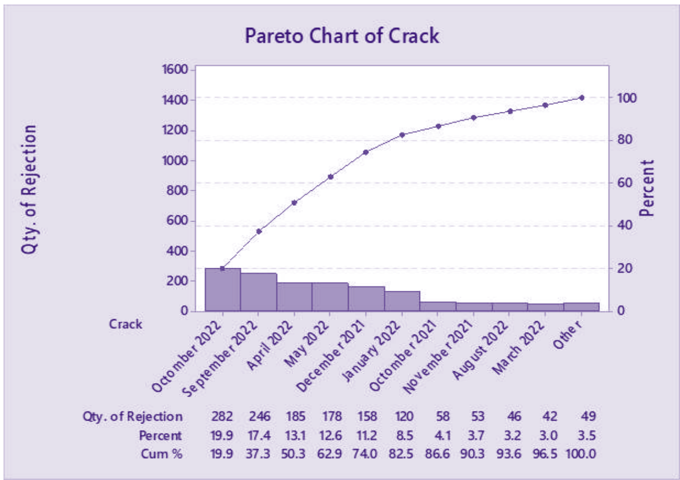
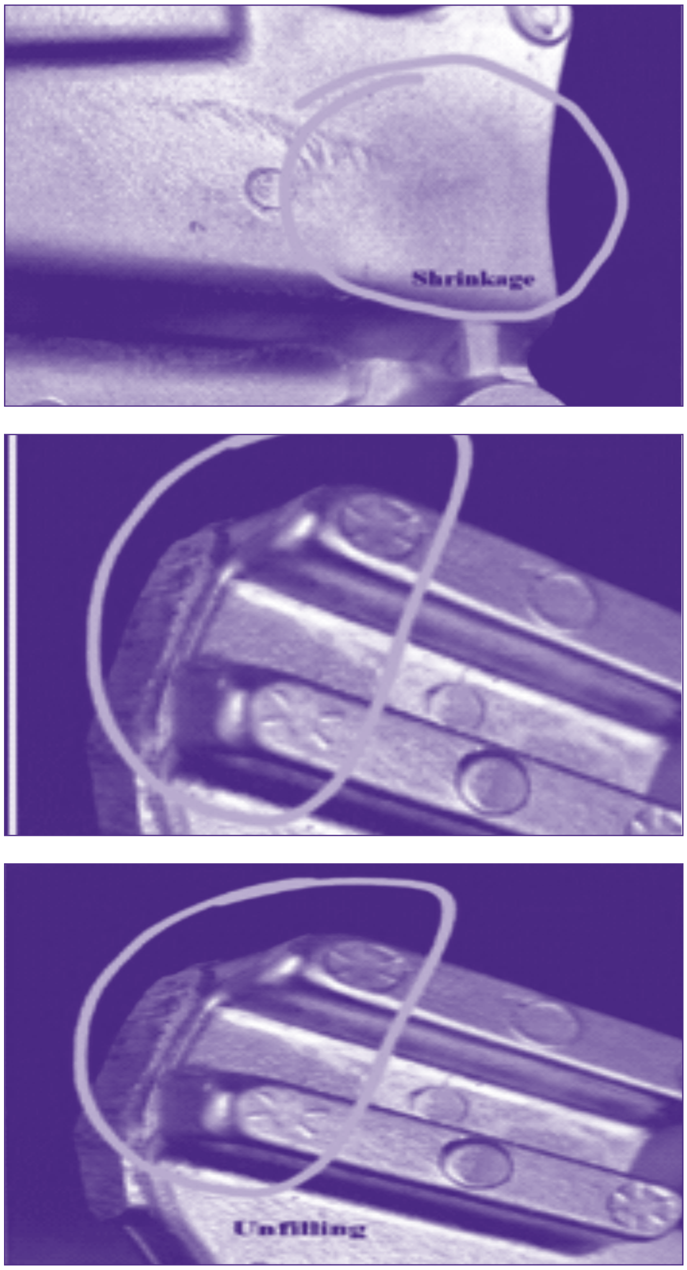


Figure 5 (d)-Pareto charts of Crack defect



From Pareto chart Figure 5 (a) we conclude that 73.6% of rejections due to shrinkage occurred in the months of January 2022, May 2022, and August 2022 to November 2022. In October 2022 month, the maximum no. of castings was rejected (1454 nos. and 16.2%) due to the shrinkage defect. From Figure 5 (b) we conclude that 72.7% of rejections due to blowholes occur in the months of August 2022 to November 2022. In October 2022 month, the maximum no. of castings was rejected (1683 nos. and 23.8%) due to the blowhole. From Figure 5 (c) we conclude that 77.8% of rejections due to unfilling occur in the months of December 2021, January 2022, May 2022, and September 2022 to November 2022. In September 2022 month, the maximum no. of castings was rejected (558 nos. and 17.8%) due to the unfilling. According to Figure 5 (d), 74% of crack-related rejections happen in the months of December 2021, January 2022, April, May, September, and October 2022. In October 2022 month, the maximum no. of castings was rejected (282 nos. and 19.9%) due to the crack defect. It was observed that from September 2022 to October 2022 months' maximum % of castings was rejected due to shrinkage, blowholes, unfilling, and crack casting defects. Figure 6 represents the images of shrinkage, unfilling, and crack defects.

Figure 6. Image of braking bracket defects



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3.3 Causes and Effect (Ishikawa) Diagram

The cause and effect (Ishikawa) diagram is one of the methods which help in the investigation of the identification of the most significant factors which causes the defect in the casting visually. Studying and observing the die casting (Gravity) process in casting industries it may be possible of some process parameters; machines and the approach of workers have a significant contribution to the rejection of the casting. In this section, we draw the Ishikawa diagram of shrinkage, blowhole, unfilling and crack defects for the identification of various causes of the braking bracket casting defects. Figure 7 represents the cause-effect (Ishikawa) diagram of (a) shrinkage (b) blowhole (c) unfilling (d) crack casting defect.

Figure 7 (a)-Cause-effect (Ishikawa) diagram of Shrinkage

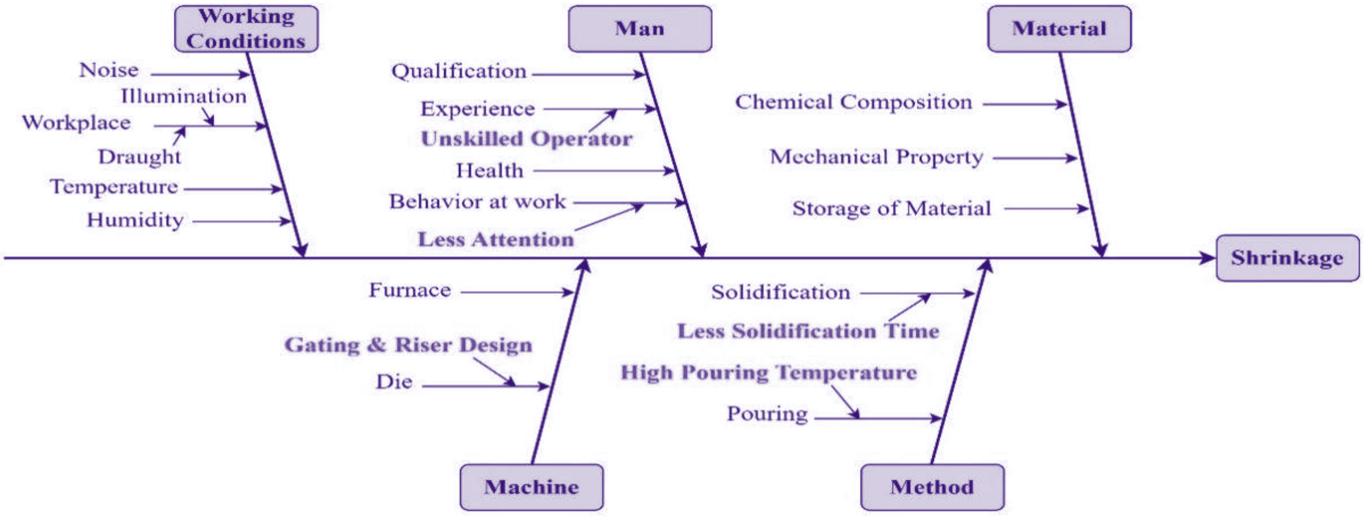


Figure 7 (b)-Cause-effect (Ishikawa) diagram of Blowhole

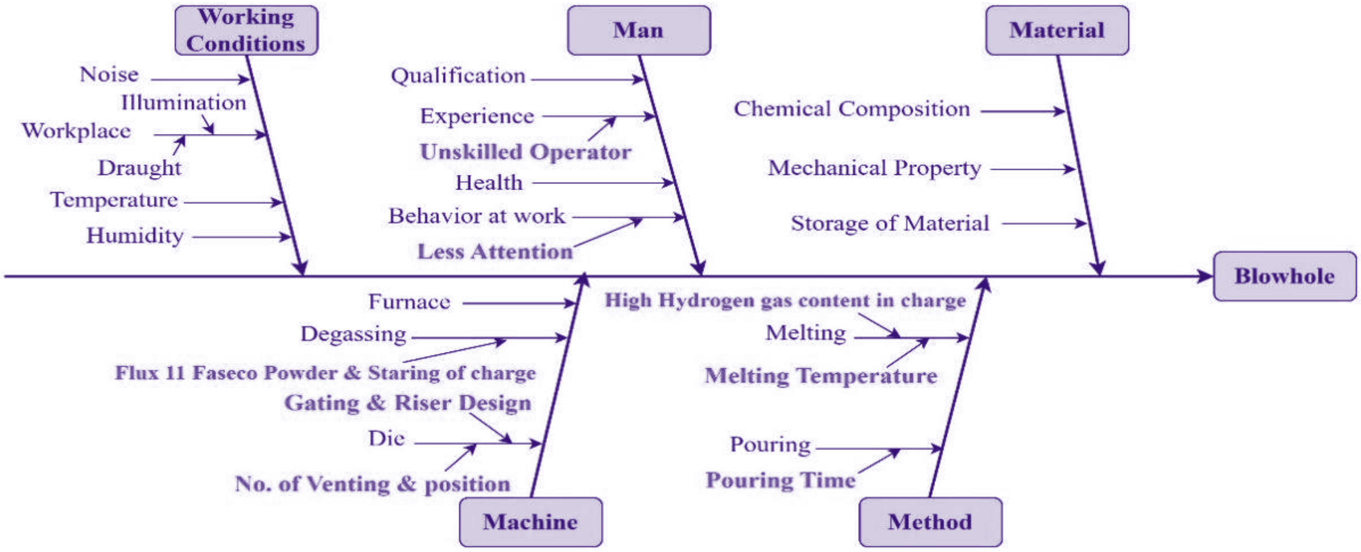


Figure 7 (c)-Cause-effect (Ishikawa) diagram of Unfilling

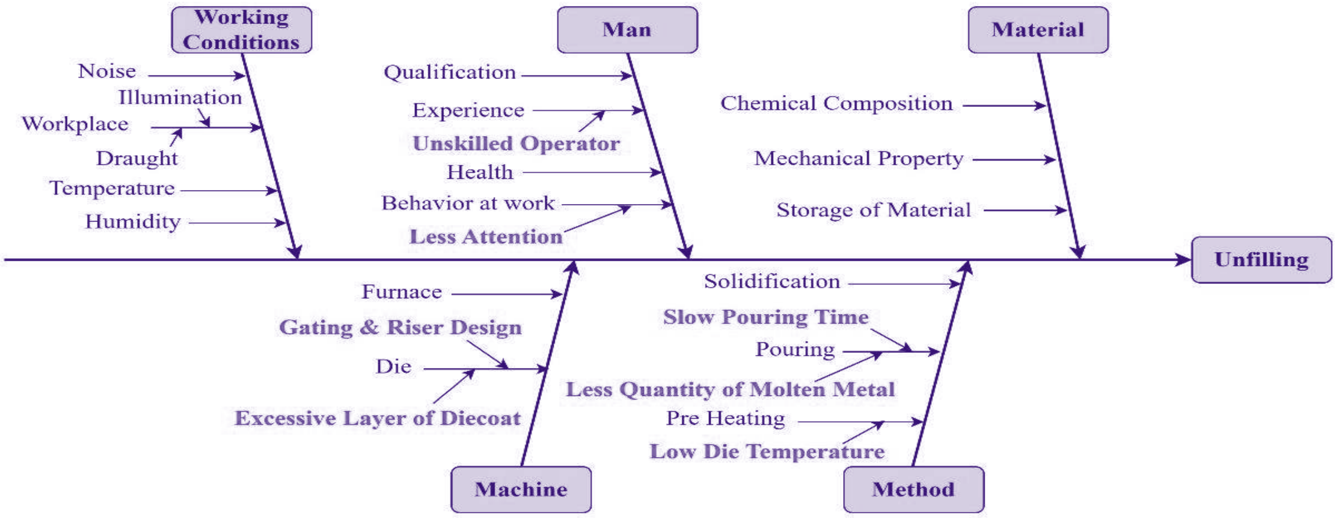
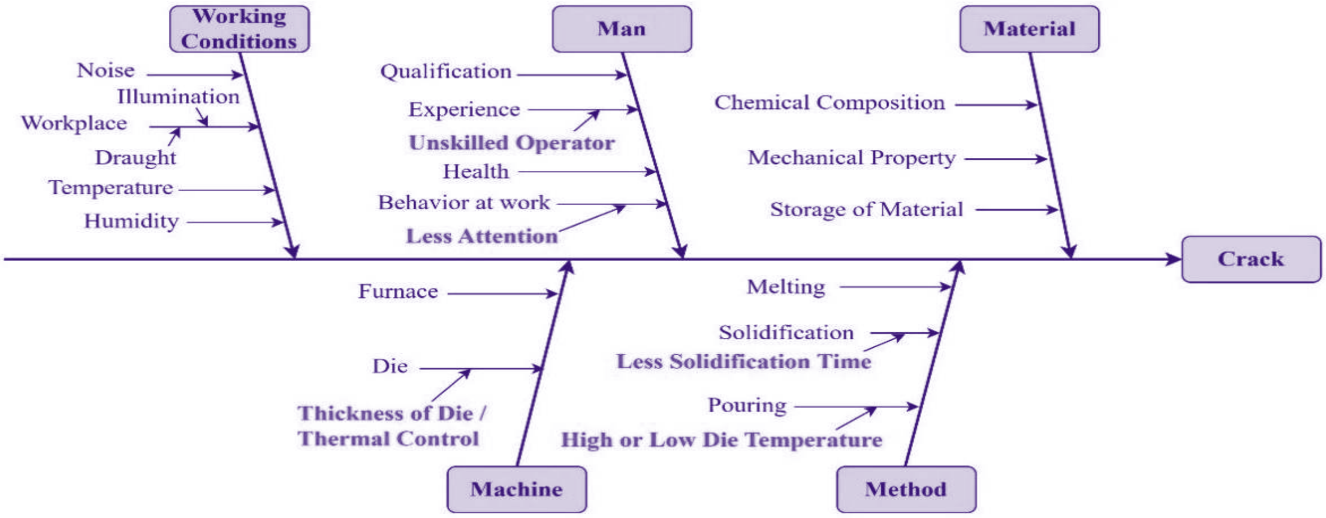


Figure 7 (d)-Cause-effect (Ishikawa) diagram of Crack casting defects



4. FINDINGS AND DISCUSSION

Figure 7 represents the cause-effect or Ishikawa diagram for shrinkage, blowhole, unfilling, and crack defects. It illustrates the no variation or change in chemical composition and material property of raw casting material and appropriate working conditions (such as workplace, atmospheric condition, and temperature) observe in the industry. Due to that reason, these two factors were not influencing a defect in the casting. Because of the unskilled and less attention of the operator towards the process parameters of casting (pouring temperature, die temperature, solidification time, etc.) at the time of production, it may have a possibility the defect occurs in casting. The method (process parameter) and machine (design of die) have the most significant impact on the various casting defect. The shrinkage is arising in the casting during the solidification process. If increasing the pouring temperature the density of molten metal was reduced. During the solidification process molten metal changes from liquid to solid phase it undergoes shrinking. If the opening of the die is before the completion of the solidification period molten metal may be shrinking. Hence, high pouring temperature and less solidification time were strongly influencing the shrinkage defect in the casting of braking brackets. During the melting process, adding less quantity of flux 11 fiasco powders in molten metal results in a high quantity of hydrogen gases dissolved in it. Such a high amount of dissolved hydrogen gas in molten metal was poured into the cavity very slowly which results in a blowhole cavity in the casting. Due to the wrong design of vents, these gases don't remove from the cavity. Hence, these have the main causes of the occurrence of blowholes in the casting. The unfilling defect occurs when there is insufficient molten metal poured into the cavity. Also, the complex design of getting and riser, excessive die coat layer, slow pouring time, and low die temperature liquid state molten metal doesn't flow smoothly towards all edges of the casting cavity, which results in an unfilling defect in the casting. Due to the high or low temperature, the die surface and liquid phase molten metal temperature difference and coefficient of thermal expansion thermal stress observed which results in the crack defect on the casting surface. The die wall thickness also has a significant impact to crack on the casting surface.

5. CONCLUSIONS

The die-casting (gravity) process where reviewed through a literature review and industrial study. From the industrial case study it was observed that the process parameters (pouring temperature, die temperature, solidification time, pouring time, etc.), design of the die (design of getting and riser system), and less attention of unskilled operator were the major affecting factors. Due to this various casting defects occurred in the casting process and will impact product quality. Plotting the cause-effect (Ishikawa) diagram the various causes of shrinkage, blowhole, unfilling, and crack defects of braking bracket casting are listed. This paper represents the possible causes of these defects occurring in the casting.

- Casting shrinkage was observed as a result of the high pouring temperature and short solidification time.
- In the presence of high contaminants such as hydrogen gases and oxides, as well as the incorrect position of venting in casting, a blowhole may form.
- Inadequate molten metal pouring into the cavity, as well as the complexity of getting and riser design unfilling, were observed.
- Cracks on the casting surface occurred as a result of high or low die temperature and internal thermal stress concentration.
- To minimalize the braking bracket defects this study strongly suggests to the casting industries simulate these process parameters through simulation software and optimize these process parameters through various mathematical modeling. This study will be helpful to the many casting industries for improving the quality of casting products, saving the cost and time, and reputation of the casting industries.

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