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Defect Minimization in Cast Parts Using Computer Aided Simulation Approach

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Abstract: Over the past two years (2023–2024), a total of 320 gear housings were manufactured at a precision casting unit located in Peenya Industrial Area, Bengaluru, Karnataka. Among these, 112 housings (about 35%) were rejected due to shrinkage porosity defects, which reduced the overall casting yield to just 52.8%. This high rejection rate caused a financial loss of₹18,75,000 during the period. Casting simulation studies confirmed that shrinkage defects in the flange roller castings originated from the existing casting method. The primary objective of this study is to reduce shrinkage porosity in flange roller castings using a computer-aided simulation approach to improve yield. A mixed research methodology was applied, combining simulation-based optimization, theoretical study, and shop floor validation. Failure Mode and Effect Analysis (FMEA) was carried out to identify potential sources of shrinkage defects. Data for the study was collected through literature surveys, direct observations, review of foundry reports, and informal interviews. For analysis, tools such as cause-and-effect diagrams, Pareto charts, and why-why analysis were employed.

1 INTRODUCTION

Casting is a process of making solid objects by pouring molten metal into a cavity of required shape and allowing it to solidify. Here's the simplified version in the same style: Casting involves different stages. These include pre-casting steps such as pattern making, core making, molding, and mold assembly. The casting process itself covers furnace charging, melting, holding, and pouring. After casting, post-casting steps like shakeout, inspection, and dispatch are carried out. Metal casting processes divide into two categories. based on mold type: (1) expendable mold - In expendable mold casting operations, the mold is sacrificed in order to remove the cast part, and (2) permanent mold - In permanent-mold casting processes, the mold is fabricated out of metal (or other durable material) and can be used many times to make many castings

2 PROBLEM STATEMENT

The involvement of several process parameters in the casting process makes the process control difficult and results in various casting defects in the products due to which the product is rejected. The foundry shop of PRECISION CASTINGS, is suffering from casting defects, reworks, repairs, high rejections, high production cost, loss of customers satisfaction, and limited market competition. The cast product in precision castings foundry is flange roller, mill roller, trash plate, and scraper plate with a rejection rate of 37.45%, 25%, 20%, and 6.67% respectively because of casting defects. Shrinkage porosity, hotspot, blowholes, sand inclusion, sand burning, cracks, hot tears, surface cracks, and pinholes are the most occurring casting defects in the cast part of the foundry. Among the products of the foundry, the most defective one with a high rejection rate is the flanged roller having 251 products in the last two years. The casting defect in the flanged roller includes shrinkage porosity, hotspot, flash, blowholes, sand inclusion, and air entrapment. The contributor to the occurrence of these casting defects in casting the flanged roller is the man (worker) material, method, molding, pouring, and casting design. The Failure Mode and Effect Analysis (FMEA) on the contributor i.e. Gating system design, feeding system, pouring, casting design, process control, molding, and venting gives the Risk Priority Number (RPN) of 648, 512, 360, 270, 252, 224, and 210 respectively. The gating system in the existing flange roller casting consumes 56.89% of molten metal, and the casting yield of the product is 53.11% below the standard for Grey Cast Iron cast product of 70-80%. Therefore, in this research work, the major contributor i.e. casting design, particularly the gating system design, for the occurrence of the casting defect, high utilization of molten metal by gating system, and yield improvement is researched. The cause and effect analysis and Why-Why analysis are conducted to determine the root cause for the poor functioning of the gating system resulting in casting defect. The computer-aided casting simulation approach is used for shrinkage porosity, hotspot, blowholes, sand inclusion, and air entrapment casting defect minimization, caused due to poor design of the gating system. Prior identification of the casting defect can save production time, and resources, reduce the rejection rate and give the advantage of taking proper measures to eliminate the defects before actual production. The foundry uses the trial and error approach for casting defect minimization in the cast parts.

3 RESEARCH METHODOLOGY

To carry out the research mixed methods (simulation - based optimization along with shop floor validation and theoretical) were implemented in this research work conducted in precision castings for achieving the objective of the study i.e. minimizing casting defects in cast parts using a computer-aided approach.

1. Data collection: data gathered from primary sources i.e. foundry observation, informal interviews, and discussion with individuals who actively involved in the topic area of the research and concerned people such as foundry supervisor, foundry skilled labour, machine shop supervisor, quality control department, and secondary sources i.e. conducting preview of literature;
2. Direct physical observation of shop-floor activities at the foundry from sand preparation to finishing casting process, for studying the existing production of the product and problem formulation;
3. Solid modelling and computer-aided casting simulation of the defective cast part using computer tools such as CATIA V5 and ProCAST for defect prediction respectively.
4. Analysis of casting defect for the selected defective component;
5. Taking photographs with the help of a digital camera were used to obtain information for the defect analysis.
6. Proposing strategies for minimizing the casting defects detected on the study cast product based on actual production and simulation results.
7. Both qualitative and quantitative analyses are performed to analyse the effect of shrinkage porosity on the selected defective components.

3.1 Research type

The research were followed an inductive approach, i.e. Inductive approach is a theory- building process, starting with observations of specific instances, and seeking to establish generalizations about the phenomenon under investigation, i.e. casting process. Inductive research goes from data to theory. In practice, both case study research and analytical conceptual research were, iterated throughout this research work.

3.2 Data collection

Data collection is the process of searching for important information and gathering it for further analysis. The data is gathered from reports (company reports), journals, procedure manuals (foundry working procedure), physical observations, informal interviews with foundry and machine shop workers, and practical tests. After collecting the raw data, the researcher analyzes and draws conclusions based on the result of the analysis.

3.2.1 Source of data

The source of data for this research work was the primary source of data and secondary source of data. The primary data are those which are collected afresh and for the first time, and thus happen to be original in character while, the secondary data, on the other hand, are those which have already been collected by someone else and which have already been passed through the statistical process**.** The primary data are collected from the case company i.e. precision castings Industry and the secondary data was collected from different articles, case company reports, books, and related paperwork.

3.2.1.1 Primary data

Foundry of precision castings is the oldest and biggest government-owned casting foundry in Ethiopia, which manufacture, spare parts for automotive, agricultural machinery, and electrical equipment. The primary data are collected from the foundry by direct observation of the casting process in the foundry workshop, and the finishing process in a machine shop. Basically, the primary data collected from the foundry are related to the study product. Main product of the foundry, products and their defect rates and rejection rate, product design and casting process design are the real-time data collected for the study product.

3.2.1.2 Secondary data

The secondary data collected from articles, books, journals and preceding's to have a core knowledge about the casting process and casting defect minimization through computer aided casting simulation for improved casting yield. It includes the following concepts sand casting process, and computer aided casting simulation and its use in casting defect minimization.

3.2.1.3 Recorded data

To show the existing problems of casting defects in the case company, different documents from the company were reviewed such as production and quality check records, and foundry operation procedures. Recorded data is one of the main sources of data and data like the amount of low-grade level, defect, the frequency of occurrence, their impact, which defect affects the company product most, and cost encored to treat the defective one, etc. are collected. Two years finished cast parts production/castings of the company recorded data are used for forming the Pareto chart in order to select the most defective cast parts and most influencing casting defect on the defective cast parts of the case company.

3.3 Data analysis

Here, the real time data collected from the foundry were analyzed. The data analysis helps to model the existing production system of a foundry for most defective cast product and to set a bench mark for further improvement on the product quality and/or product yield through casting defect minimization. Overall, data analysis helps to answer the research questions. The casting defect analysis conducted using computer aided casting simulation, why-why analysis and cause and effect diagram for determining the root cause of the casting defect on most defective cast product of the foundry.

3.4 Literature Review
A review of literature is conducted on the area of defect minimization, gating system design and optimization, computer-aided casting simulation, and its contribution in defect minimization of cast part are reviewed, among this literature those which related to defect minimization is used as one of the secondary data sources. All available books, journals, case studies, previous research works were surveyed in order to have a clear understanding of the subject matter.

3.5 Problem formulation
Selection of the most defective product of the foundry for further study is conducted based on the data collected. The major casting defect in the most defect product is determined using the Pareto charts. The casting result for the casting of the product is in good agreement with the simulation results for simulation of the existing casting process for the defective cast part. Defective product, major casting defect on the defective product lie a foundation for defining the problems for further study. Cause and effect diagram, Why- Why analysis, and simulation of the existing casting process of the defective products are tools and/or approaches to define the study problems.

3.5.1 Cause and effect diagram
The cause and effect diagram was used to determine the root cause for the casting defects. Man, material, casting design, pouring of molten metal, molding and casting methods are the main categories for analyzing the root of the casting defects.

3.5.2 The why-why analysis
The why-why analysis was conducted for the major contributor i.e. the gating and feeding system design, of the shrinkage casting defect. Step wise asking of the "why" to each happening of action five times, the root cause behind the product nonconformance to the specified quality level is determined.

3.6 Problem solving
3.6.1Casting simulation
Based on the collected data the cast parts were simulated using the ProCAST 2019 version for defects prediction. Five simulation is conducted i.e. one simulation with the existing production system, and three simulation with a proposed gating system. The simulation results for the existing casting process of the flange roller were analyzed and further improvement in the gating and feeding system are applied to minimize the casting defects.

3.6.2 Failure Mode and Effect Analysis
The Failure Mode and Effect Analysis (FMEA) was conducted to determine the potential cause for the occurrence of the major casting defect. The core base for carrying out the FMEA are the major contributor for occurrence of shrinkage casting defects from the cause and effect diagram, i.e. casting design, man, method, material, molding, and pouring system.

3.6.3 Proposing new gating system
Based on the analysis result of the existing casting process for the flange roller, the cause and effect diagram, the why-why analysis for the major contributor and the FMEA results new gating system is proposed to minimize the casting defects in the product.

3.7 Validation and result justification
The proposed gating and feeding system *(Gap I, & II)* are validated by casting the study cast part in the case company. The casting defect predicted by the casting simulation is compared to the actual shop floor casting of the case product. Along the validation of the proposed gating system of flange roller, the FMEA was implemented. Eventually, result of the study is justified based on casting yield improvement, casting material utilization, and shrinkage casting defect minimization, according to the existing casting approach of case cast part.

RESULTS AND DISCUSSIONS

4.1 Introduction
This final chapter presents the MSc thesis on "Defect Minimization in Cast parts using Computer-aided Simulation Approach" with discussions on major findings and regarding the applied methodology. The findings will be evaluated against the purpose i.e. significant of the research, the research questions, and the theoretical background. Practical validation of flange roller casting based on the proposed gating system and simulation result for defect minimization of the cast part is presented. Last of all, the MSc thesis will be concluded and suggestions for further research ideas based on the validation of the casting of one flange roller using proposed gating system.

4.2 Casting Defecates in Precession Casting Products

The foundry of precision castings is currently producing a limited number of products. Among these products mill roller, scraper plate, trash plate, and flange roller for sugar industries are some, and the production data is given in table 14. Foundry suffers from weak quality and productivity due to a huge number of process parameters, lower automation, and shortage of skilled workers which result in product rejection, precision castings foundry as well. The rejected product in precision castings foundry, are due to casting defects, which do not satisfy the customer requirement i.e. sugar industries. It is impossible to cast a defect free part, instead the defect in cast part are minimized using different quality control tools. Casting defects in cast parts do not occur in an accident, instead improper design, and limited process control leads to product rejection. In a casting foundry, a product has basically three processing stages: design stages, casting process stages, and finishing stages. From critical observation in precision castings foundry type of casting defects which result in product rejection, are shrinkage cavity, porosity, blowholes, mold erosion, air entrapment, sand inclusion, and over and under dimension. The defects history from 2010 (E.C) onwards was collected from the quality control department of the factory given in table 14. From this table the defect record for the rejected products, indicate that poor casting design *(design of gating and feeding system)*, poor process control, limited casting capacity of the operators and skills are the contributing factors for the cause of casting defects, resulting in product rejection. Molding an improper mold assembly being a major contributor for casting defect, needs a great attention while in operations. Inadequate process control and improper gating system design causing inefficient pouring and allow air entrainment causing shrinkage and porosity casting defects.

Table 13: Defect history for cast parts, (Source: precision castings Quality Control Department.)

Types of defects	Major Cause.
Shrinkage.	Under fill, gating system, pouring,
Porosity , Incomplete Casting	Pouring, air entrainment, melting
Under dimension, and mismatch.	Molding and melting.
Cracking	Molding, material problems.
Miss run/miss match.	Poor mold assembly.
Core shift.	Mold assembly, improper pour print usage.
Under dimension.	Less molten metal.

4.3 Defect identification in cast parts

RQ-1: *What product is having high rejection rate due to casting defect and frequently occurring casting defects on the same product along with cause of occurrence?"*

Foundry real time production data, production plane, casting design of foundry product, and recorded data are used as an input for answering the first research question. Most defective products, defect type and defect rate, and foundry yield are the determined output (labeled "A" in the flow chart of figure 13. Answering RQ-1 helps to meet the first specific objectives of this research.

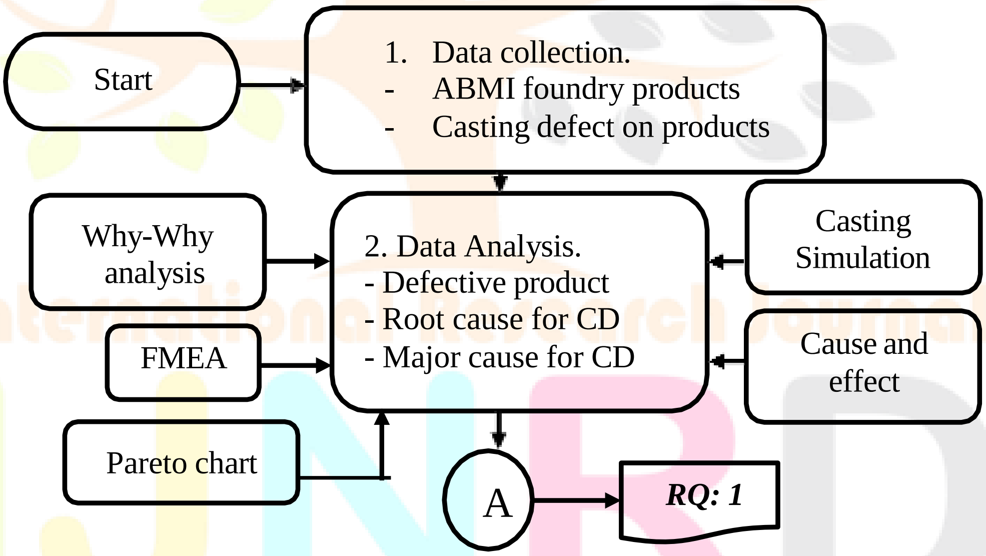

Figure 13: Flow chart for answering RQ: 1

4.4 Defective product and major casting defects –study product selection

The product selected for further study is a product with highest rejection rate. From *table 15*, the most defective product is the flange roller and mill roller, with high rate of rejection 37.45% and 25% respectively. The cause of casting defects for these products i.e. flange roller, which result in its rejections are pouring, molding, gating system design, pattern and poor process control technique in the foundry production process. The defect on the mill roller is compromised, i.e. the defect found on the mill roller like porosity, shrinkage are compromised and/or modified through welding the defected area and grinding operations.

The flange roller product is ordered by governmental sugar industries of Ethiopia, such as Finch Sugar Factor, (F.S.F), Mathura Sugar Factory (MSF). A total of 750, are ordered in 2011, and 2012 E.C. from Ethiopian sugar industries. The foundry manufacture or cast 251 flange roller, from which 94 products are rejected due to casting defects on the products. The total cost for manufacturing one piece of flange roller is *1,798.16 EB,* therefore a factory loses 169,027.04 *EB* from the five rejected flange roller.

Table 14: Foundry production data for varies Product, *(Source: precision castings Quality Control Department.)*

Product.	Customer order.	Total production.	Total tested product.	Quality product.	Rejected product.	Rejection rate.	Total production cost, EB
Mill roller	15	4	4	3	1	25%	320,798
Scraper plate	30	15	15	14	1	6.67%	18,107
Trash plate	25	15	15	12	3	20%	49,850
Flange roller	750	251	251	157	94	37.45%	1,798.16
Total:	820	285	285	186	98	22.28% avg.	390,543.16

Flange roller has high rejection rate, i.e. 37.45% due to casting defects, discussed in section 2.2.5 of chapter two, hence it is selected for further study of minimizing casting defect occurrence using a computer-aided casting simulation approach. The major rationale due to which the product *i.e. Flange Roller* is selected for further study are:-

1. High defect and high rejection rate as compared to other cast parts in precision castings (37.45%),
2. Low rate of product delivery to customer or high delay time (20.93%),
3. High production cost loss due to product rejection (169,027.04 *EB)*, and
4. For testing the proposed gating and feeding system (validation) due low production cost (1,798.16 EB per flange roller) as compared to other product of the foundry.

4.4.1 Casting defect of flange roller product

The foundry has a data recording problems that makes a continuous process improvement difficult. If a data is not recorded properly, it definitely makes future process improvement difficult. The type of casting defect with their corresponding defect rate in the study product of the foundry i.e. flange roller are given in table 16. The defect data are, collected from the rejected product from the last two years production period. From the rejected flange roller 60% flange rollers *(57 flange roller from 94)* are rejected due to the shrinkage casting defects.

Table 15: Casting defect on flange roller, *(Source: precision castings Quality Control Department)*

product	Total production	Casting Defects								Total, (%)
		Shrinkage	Porosity	Hot spot	Air entrapment	Mold burn	Cold shut	Mismatch	Misrun	
Flange roller	20	√	√	√	√	--	--	--	√	100%
Defect %		60	20	15	2	--	--	1	2	

4.4.2 Pareto chart for casting defects on flange roller

The purpose of the Pareto chart is to highlight the most important among a set of casting defect, and used to carry out casting defects analysis

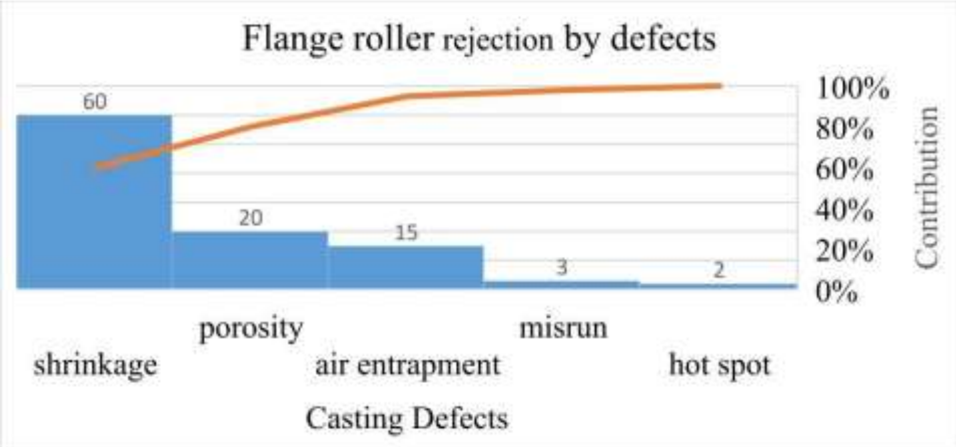

Figure 14: Flange roller rejection by defects

From the Pareto chart the major casting defect is the shrinkage porosity, blow holes and sand inclusions casting defect, causing the high rejection rate of flange roller, high rework cost. Hence, in this research work casting simulation approach is used to minimize basically the major casting defects, i.e. shrinkage porosity defects, in flange roller cast part of precision castings. Along with, hot spot, air entrapment, and misran casting defects are analyzed. Shrinkage porosity casting defects for flange roller, mill roller, trash plate, and scraper plate cast parts of precision castings foundry are depicted in figure 14, a, b, c, and d respectively.

a). Flange Roller

b). Mill Roller

C). Trash Plate

D). Scraper Plate

Figure 15: Shrinkage casting defect on different products of precision castings*(Observation)*

4.5 Shrinkage defect analysis

The precision castings foundry face a casting defect challenges in casting the flange roller, and hence low casting yield. The main objective of the study is yield improvement of the flange roller casting process through defect minimization. To this end the existing casting system of flange roller is studied and the root cause for the casting defect are analyzed using cause and effect diagram, why-why analysis for yield improvement. The yield improvement approach based on the existing casting system and simulation result is implemented through conducting the Failure Mode and Effect Analysis (FMEA).Currently the most used casting defect analysis methods according to, are Computerized Aided Simulations (CAE), Holistic approach, Historical analysis, Pareto analysis, cause-effect diagrams, design of experiments, if-then rules (expert systems), and artificial neural networks (ANN). Shrinkage porosity, sand inclusion, and blowhole casting defect of the flange roller is analyzed using root cause analysis and why-why (5-Why) analysis tools to determine the root cause of casting defect. The FMEA is carried out during the analysis to be implemented during the validations stages

4.5.1 Cause and effect diagram

The cause and effect diagram are drawn for finding the root cause of the casting defects. While conducting the cause and effect diagram, man (worker), methods, casting design, material, molding and pouring are the major categories of causes of the problem (phenomenon) in the given production of flange roller. The cause and effect diagram for occurrence of the major defects in castings is focused on factors affecting the formation of sound casting from molten metal to the final product.

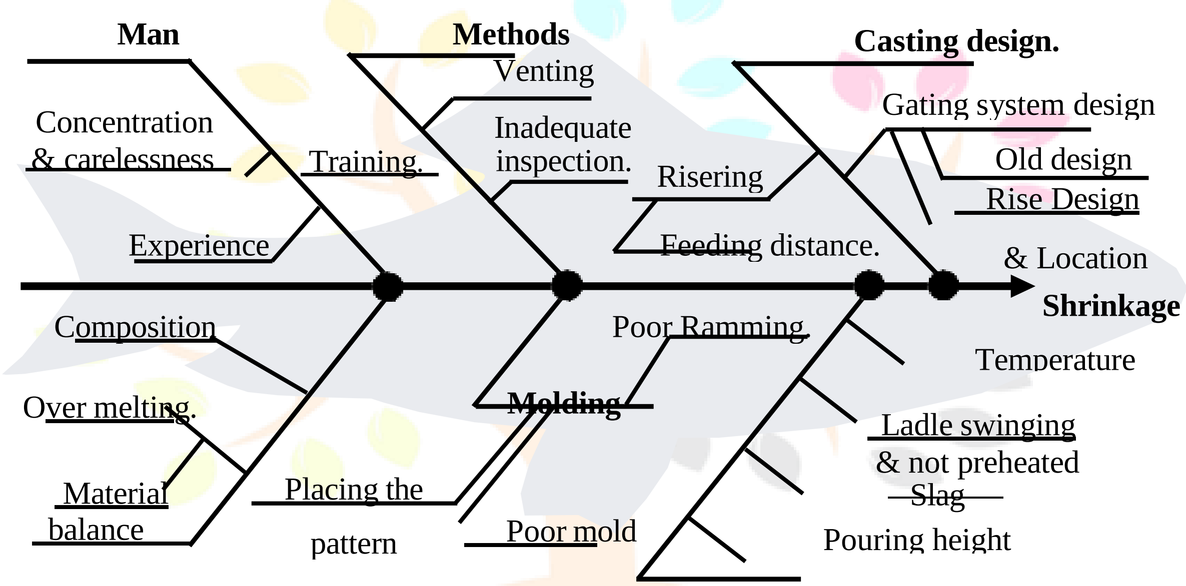

Figure 16: Cause and effect diagram for occurrence of shrinkage defect *(Developed based on foundry observation).*

From the above root cause analysis, the major contributor for the shrinkage casting defect are poor design of gating and feeding system, inadequate pouring mechanism, material inspection, and composition, poor process control, and carelessness of workers during molding, fettling operations.

4.5.2 Why - Why analysis for gating system

The root cause of the casting defect from the cause and effect diagram is analyzed using the why-why analysis technique. Due to the volume, time and cost limitations, the study will includes the part of the Ishikawa diagram i.e. gating system design which are the major contributor for the defects or containing the key cause of non-compliance. The why-why analysis is done for determining the root cause of the casting defect ***(Adhikari, S., Sachdeva, N., & Prajapati, 2017)***[86]**.** In this particular case, the why-why or 5-why, analysis is conducted for determining the root cause for the major casting defects caused due to the non-compliance of the gating and feeding system. A well-designed runner and gating system is very important to produce good quality an sound castings by providing a homogenous mold filling pattern ***(Ramnath et al., 2014)***[87]. The flange roller of PRECISION CASTINGS has a poor gating system resulting in casting defect in the product. In-adequate pouring mechanism, and poor gating and feeding system design are the major cause. The root cause for the occurrence of shrinkage casting defect in flange roller is analyzed in figure 15. Shrinkage is a type of casting defect resulting due to formation of shrinkage cavity as such due to lack of design and insufficient feed metal ***(Juriani, 2015)***[88], shrinkage is a solidification related casting defects in casting process.

The major aim for conducting the why-why analysis is to determine the root cause of casting defect. Problem definition: the casting of flange roller cast in precision castings foundry is subjected to casting defect resulting in product rejection. One of the major casting defects detected in flange roller products is the shrinkage casting defect. The flange roller product has a rejection rate of 37.45%. The challenges of casting defects are to be identified and minimized for effective castings ***(Chelladurai et al., 2020)***[14]

To minimize this casting defect it is better to know the root cause of the casting defect. Improvement in casting quality is the process of finding the root cause of occurrence of casting defects in the rejection of casting and taking necessary steps to reduce the defects and hence rejection of casting ***(Patil, 2014)***[89]**.**

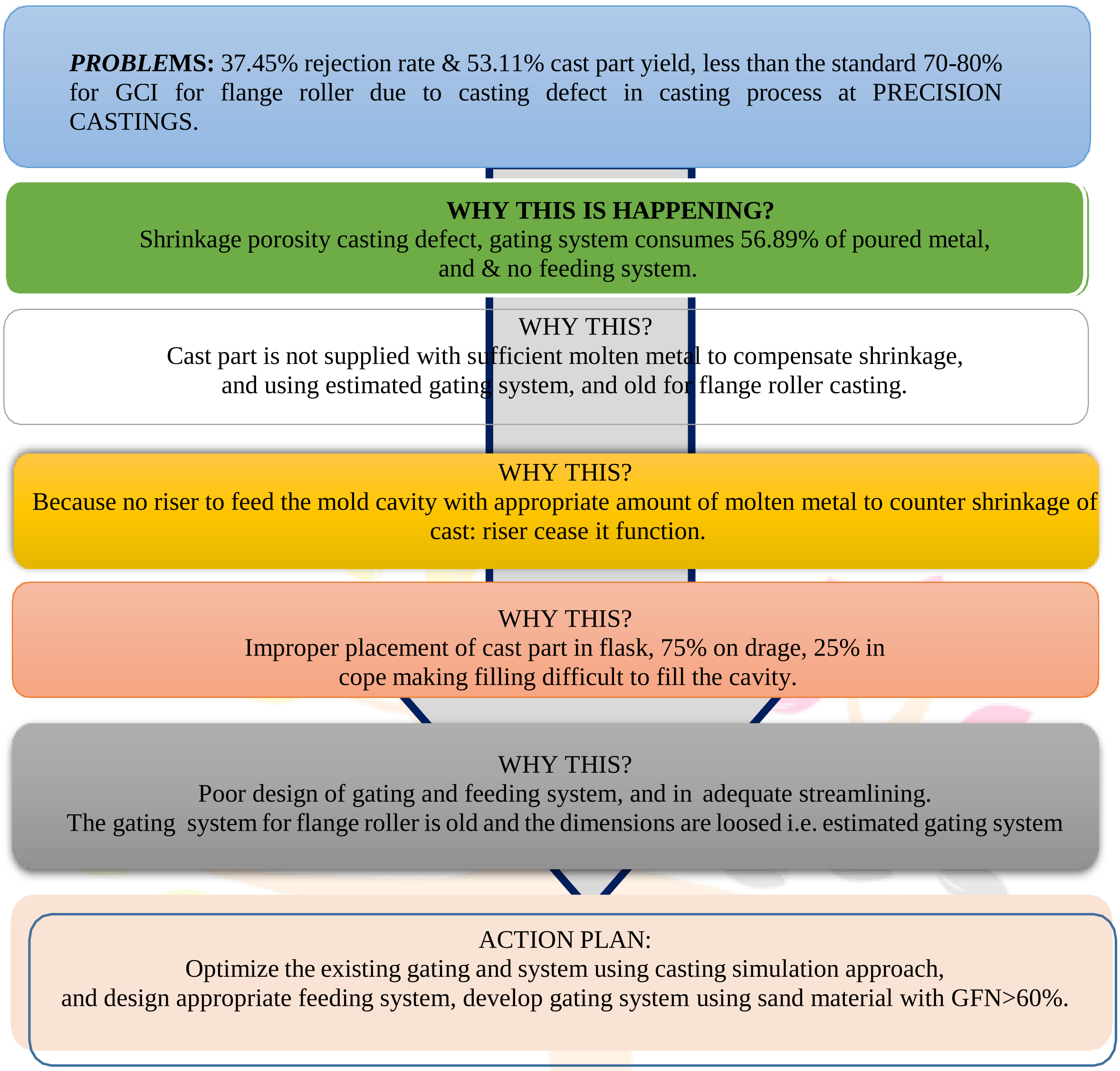

Figure 18: Why - Why analysis of shrinkage casting defect.

From the why-why analysis of Figure 18*:* we can understand that the root cause for the shrinkage defect is the poor design of the gating and feeding system. Hence, the poor design of the gating and feeding system in flange roller castings, results in product rejection. From the cause and effect analysis and the why-why analysis of the flange roller casting in precision castings, it is understood that, the major cause for the rejection of the flange roller in precision castings is the poor design of the gating and no use of feeding system. Therefore, the gating system need to be optimized, and redesigned so as to have a sound flange roller casting and eliminate rework of the cast part.

4.6 Analysis of the gating and feeding system

The analysis of the gating system is carried out using simulation approach. The algorithm for developing for designing the dimensions to the new gating system. The algorithm has three basic phases. Existing gating system dimensions, simulating the casting process with the existing gating system and optimizing the dimensions for the minimized major casting defects, and designing the new gating system based on the simulation result.

4.6.1 Gating system in sand casting process

In modern day's industries, greater emphasis is placed on cost reduction, optimizing profits, quality of product, customer satisfaction, and staying ahead of the competition ***(Kumar, 2003)***[90]**.** This conditions are critical for foundry industry, and hence, the foundry must have a minimum rejection rate, minimum casting defect, shorter production time. From ***(Singh et al., 2016)***[91] there is a requirement for casting units & foundries to deliver components with less rejection rate i.e. short lead time, for achieving this, the gating framework is assuming an essential part in the field of quality therefore, optimization of gating framework in metal casting delivers the error-free components.

A gating system is the conduit network through which liquid metal enters a mold and flows to fill the mold cavity, where the metal can then solidify to form the desired casting shape ***(D.M. Stefanescu, 2001)***[92]**.** The design of gating system occupies a very important proportion in the design of the entire casting process ***(Wang et al., 2018)***[93] and gating system design needs due consideration, from ***(Panchal et al., 2015)***[94] poor design of gating and risering system result on different defects such as shrinkage, crack, porosity, hot tear. A well-designed feeding and gating system is very important to produce good quality die castings by providing a homogenous mold filling pattern ***(Ramnath et al., 2014)***[87].

4.6.2 Basic requirement of gating system.

Gating systems refer to all those elements, which are connected with the flow of molten metal from the ladle to the mold cavity. Gating system require the proper design of gating system i.e. correct design pouring cup, sprue, sprue base well, runner, runner extension and in-gates for sound casting. According to ***(Apte, 1978)***[95]**,** a gating system should introduce the metal into the mold cavity in such a manner that avoids the formation of casting defects such as laps, sand erosion, and spalling, slag or dross inclusions, gas cavities and shrinkage, and at the same time, the yield of the casting should be maintained as high as possible and the cost of gate removal minimized. Each part of the gating system has its contribution to defect occurrence and casting defect minimization. The pouring cup deliver metal from ladle to sprue, establish proper flow of molten metal (Kumar, 200390; Muzakki et al., 202196), sprue connect pouring cup to runner, avoid molten metal turbulence (Kumar, 200391; Muzakki et al., 202196), sprue basin is a reservoir for the molten metal at the bottom of the sprue to reduce the momentum of the molten metal (Kumar, 2003)90 runner deliver molten metal from sprue to in-gate (Kumar, 2003)90, runner extension is used to trap the slag in molten metal (Kumar, 2003)90, and in-gate lead the molten metal from the runner to mold cavity (Kumar, 2003)90**.**The current gating and feeding system used for casting the flange roller is directly measured, and simulated using the foundry real-time data for casting defect for further design improvement. The components of the gating system are shown in the Figure 20.

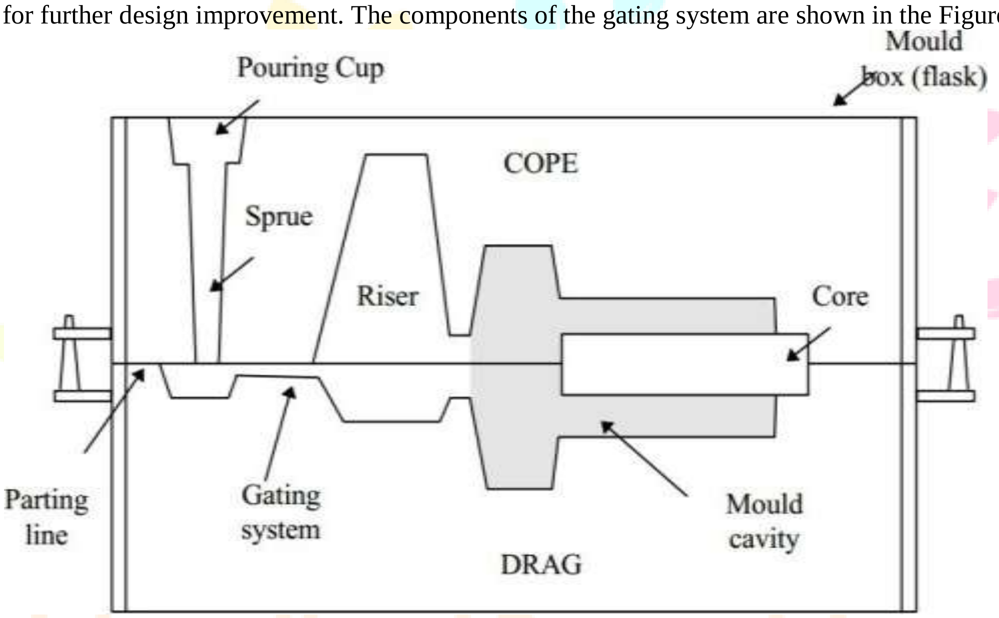

Figure 20: Schematic of the components of the gating system ***(P. J. Mandaliya & J. T. Dave, 2013)***[97]

The existing casting process in the foundry of precision castings has only the gating system, i.e. no feeding system (riser) is used. The arrangement of the gating system for casting the flange roller is shown in Figure 21. The gating system for casting the flange roller include pouring cup, sprue, sprue basin, runner, and in-gates (two in-gates). These gating system is not properly designed for the flange roller, according to the foundry men’s an estimated gating system is used for casting. This is a major problems in the foundry of precision castings, besides to this a poor process controls are practiced contributing for the casting defects.

Figure 21: Existing gating system components arrangement (left side), and measuring the gating system components (right side*)*

4.7 Casting simulation approach

4.7.1 ProCAST Casting Simulator

As discussed in section 1.2.2. of chapter one, casting simulation started early 1980s as a result of software and hardware development in computer ***(Jolly, 2002)***[8] and bring an improvement in quality of casting products. There are number of casting simulator developed for casting foundry. List of casting software along with the vendor company is given in Table 16.

Table 16: List of Casting simulation software and vendor

Casting simulation software	Vendor
AutoCAST	Advances Reasoning Technologies P.Ltd., Mumbai
CAPCAST	EKK, Inc., Walled Lake, Michigan, USA
CastCAE	CT- Castech Inc. Oy, Espoo, Finland
MAGMASOFT	MAGMA GmbH, Aachen, Germany
Nova-Solid/Flow	Novacast AB, Ronneby, Sweden
ProCAST	ESI Group, Paris, France
FLOW-3D Cast	Flow Science, Inc., 683 Harkle Rd, Santa Fe, NM 87505, USA
SOLIDCast	Finite Solution Inc., Hamilton, OH, 45013, USA
MAVIS	Alphacast Software, Swansea, UK
JSCast	Komatsu Soft Ltd., Osaka, Japan
SIMTEC	RWP GmbH, Roetgen, Germany

*Source: **(Behera et al., 2010[98]; Khan, 2018[99]; Ravi, 2008[100])***

Each software provides a set of capabilities for sound castings. For selecting the casting software, the casting simulating software are compared based on different perspective such as solution method, hardware requirement, user input, steps in simulation, processing time ***(Behera et al., 2010)[99]***, and accuracy of results, process of mold filling, solidification process, and prediction of defects and mechanical properties ***(Vasková et al., 2011)[101]***.

Table 17: Casting processes simulated by selected software

Casting Process	Continuous Casting	HPDC	LPDC	GDC	IC, Shell Casting	Sand Casting	Squeeze casting	Centrifugal casting	LFC	Tilt pouring
AutoCAST				√	√	√				
CAPCAST		√	√		√	√	√			
CastCAE		√	√	√	√	√				
MAGMASoft		√	√	√	√	√		√	√	√
Nova-Solid/Flow		√	√	√	√	√		√	√	√
ProCAST	√	√	√	√	√	√	√	√	√	√
Flow-3D Cast	√	√	√	√	√	√	√	√	√	√
SOLIDCast			√	√	√	√				

*Source: **(Khan, 2018)[99]***

ProCAST, Flow-3D Cast, MAGMASoft, and Nova-Solid/Flow can simulate most of the metal casting processes observed in casting foundry Table *17*. ProCAST provide a lot of information such as microstructure, thermal stress, strength, hardness of the cast product as compared to other commercially available casting simulating software besides to these, ProCAST provides full flexibility to study the effects of gating and riser system design, filters, chills, exothermic sleeves on processing and quality of cast products ***(Khan, 2018)[99]***, hence, the top notch software, ProCAST is selected for simulating the flange roller cast part of precision castings for defect predications.

This study focus on shrinkage and porosity defect minimization on the flange roller of precision castings. Since shrinkage and porosity casting defects are related to filling and solidification process of casting, simulation approach of defect minimization is used. It is stated in ***(Nimbulkar and Dalu, 2016)[102]***, that the use of casting simulation software like ProCAST can able to eliminate the defects like shrinkage, porosity and others in the casting process. It also helps in improving the yield of the casting and at the same time optimization of gating system is, done. The simulation for casting defects are conducted based on the real data from the precision castings foundry, and software. Simulation include mold filling and casting solidification, useful for optimizing gating and risering systems, respectively.

4.7.2 Casting simulation, ProCAST procedure

The 3D model of the product in STP format, mold material, initial mold temperature, cast material, are the main input to the computer-aided casting simulation software and filling velocity, filling time, mold erosion, location of casting defect, solidification time, filling time, and incomplete filling are the expected output for casting simulation. Besides to this, visualization of mold filling, casting solidification, and further cooling to room temperature (Ravi, 2008)100 are observed during casting simulation. The detail procedure for casting simulation using ProCAST 2019 is given in Appendix B.

4.8 Casting simulating the flange roller

The procedure for casting simulation is shown in below flow chart:

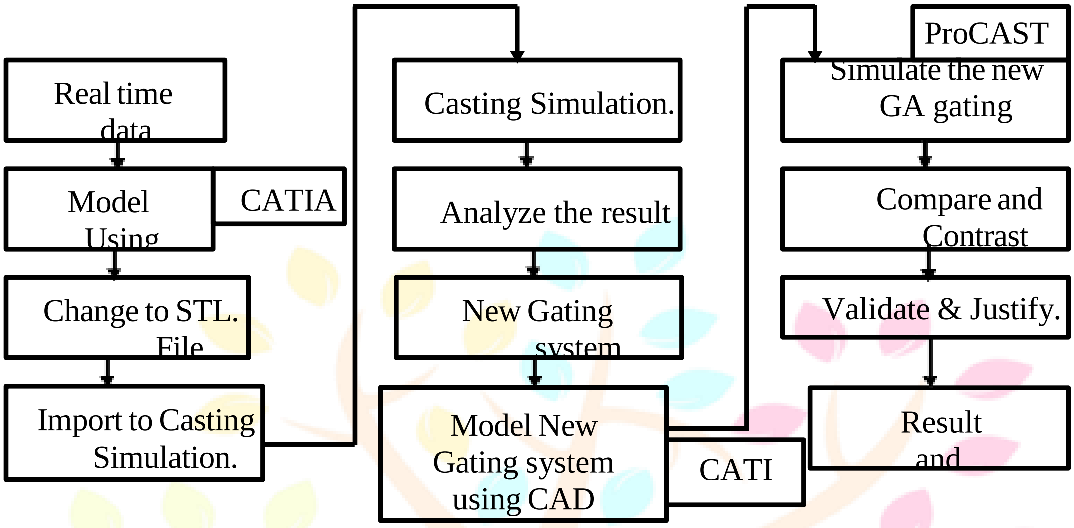

Figure 23: Casting simulation procedure for Flange roller

4.8.1 Simulation of existing flange roller casting

4.8.1.1 Simulation setups

The flange roller casting simulation is carried out using ProCAST 2019 casting simulation software. A total of five simulations are conducted. The existing casting process of the flange roller are simulated using the ProCAST 2019 casting simulating software. The casting assembly (casting setup) of the flange roller and pattern for flange roller and core print is given in figure 24. During casting the flange roller a core *(N.B. in precision castings core made from the molding material)* is used. The core is place at a center inside the mold cavity using core print.

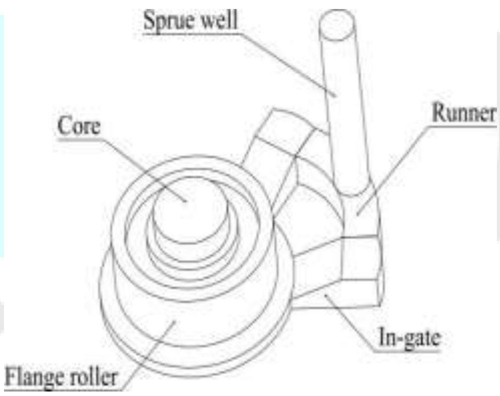

Figure 24: Pattern for flange roller and core print *(left side)* & Existing casting arrangement for flange roller casting *(right side)*

4.8.1.2 Geometric modeling the castings

The existing casting system of the flange roller has five gating and one feeding system basic components, these are the pouring cup, sprue, sprue basin, runner, and in-gate and, the runner respectively. The existing gating and feeding system for casting the flange roller is directly measured, table xxx. The gating and feeding system dimension include the allowance, for finishing operations in machine shop i.e. shrinkage, machining, volumetric, and draft angle allowance.

Before simulating the flange roller, the 3D modeling of the flange roller, the gating, and feeding system are developed using CATIA V5 software *(see Appendix C)*.

Table 18: Dimensional summary of the existing gating and feeding system
, *(Source: (Actual measurement in the precision castings foundry))*

Gating system: Sprue, sprue well, runner, in-gate

Sprue			
Upper diam.	Bottom diam.	Height, H	Height, H
40	30	130	130mm
Sprue well			
Upper Diam.	Lower Diam.	Depth, mm	Height, H
30	10	10	10mm
Runner N.B. In the existing casting of the flange roller, curved runner made manually on molds, i.e. no designed runner (an estimated runner).			
In-gate			
Length	Thickness	Width	Height
86.31	45	45	30,9.78
Flask (cope and drag)			
42mm	1mm	42mm	Rectangular

The flange roller has a hallow shape with diameter 70 mm, hence during casting the flange roller core a vertical core is used. The core print for placing the core is made from sand, during molding.

4.8.2 Casting material database

The material for casting the flange roller in precision castings casting foundry is DIN 1691 GG25 Grey Cast Iron with a base metal of Iron (Fe), and Carbon, Silicon, Phosphorus, Sulphur, and Manganese as a constitutes. Sliding parts, and pulley, and hydraulic distribution blocks (good machinability) are the main applications of is DIN 1691 GG25 Grey Cast Iron. General chemical composition of the GCI is given in Table *19*. The worldwide equivalent for this material is EN-GJL-250(EN-JL1040) in Europe.

Table 19: Chemical composition of GCI

Constituents	Symbol	Composition	Measure	Foundry composition
Carbon	C	3.00-3.25	%	3.24
Silicon	Si	1.85-2.10	%	1.66
Manganese	Mn	0.40-4	%	0.81
Sulphur	S	0.12Max	%	0.009
Phosphorus	P	0.25Max	%	0.014
Iron	Fe	Balance		94.267

4.8.2.1 Properties of simulating material

Gray cast iron (GCI) is traditionally chosen in many industrial applications because of its flexibility of use, good castability, low-cost (20–40% less than steel) and wide range of achievable mechanical properties ***(Collini et al., 2008)***[103]. GCI is one type of Cast Iron (CI) under ferrous metal, ferrous metal are those metal having Iron (Fe) as their main constituent ***(Khurmi, R. S., & Gupta, 2005)***[104].

4.8.2.2 Physical properties

Table 20: Physical properties of DIN 1691 GG25 Grey Cast Iron

Density	7.2
Thermal specific heat capacity	460 Ja 200℃(Kg. K)
Electrical resistivity	7.3E − 7 at 20℃

4.8.2.3 Mechanical properties

The mechanical behavior of a material reflects the relationship between its response or deformation to an applied load or force ***(Callister and Rethwisch, 2000)***[105]. Important mechanical properties are strength, hardness, ductility, and stiffness.

Table 21: Mechanical properties of DIN 1691 GG25 Grey Cast Iron, (*Source: precision castings, Quality Management Department*)

Tensile strength	σB	250
Elongation	A	0.3-0.8
Permanent limit of elongation	σbB	450
Compressive strength	σdB	950
Brinell hardness	HB30	180-240
Elasticity module	Eo	*10
Shear stress	σaB	290

4.8.3 Boundary conditions and inputs for simulation.

Setting a boundary conditions is assigning the material for the casting, the casting components, and giving the heat transfer interface between each components, based on the material assigned to the components. The inpute data for simulating the flange roller using ProCAST 2019 casting software is given in Table 22.

Table 22: Input parameters to casting simulation in ProCAST, *(Source: Based on precision castings foundry data.)*

Input parameters	Specific name
Alloy element	GCI Grade 25
Mold material	Silica sand
Pouring time	10Sec.
Alloy element temperature	1,300℃
Mold Initial temperature	35℃
Heat transfer coefficient between casting and mold	1000k (*Software*)
Mold cooling	Adiabatic air cooling
Pouring method	Gravity pouring
Core	Sand

4.8.3.1 Casting process detail.

Flange roller casting is conducted based on the customer order. The casting process starts from designing the casting process, and ends with machining operations. Designing the casting process of the cast part is prepared by the design section of the foundry along with developing the detail 2D and 3D drawing of the cast part and, finally transferred to the foundry shop. Based on the design the foundry men prepare the pattern considering finishing allowance in machine shop i.e. shrinkage, machining, draft angle, and volumetric allowance. During set-upping the casting process for flange roller, the researcher consider two prominent problems, i.e. poor process control and using an estimated gating and feeding system for new part casting which is inappropriate and resulting in casting defects on the cast part.

After the completion of the pattern preparation, mold is prepared (manual molding process) using silica sand (Bentonite sand binder is used) on a flask (cope and drag). The mold cavity is on the cope and the gating and feeding system is on a drag. After assembling the core and drag, and the next stage is melting and pouring into the mold cavity. The raw material for melting in a furnace is prepared from the scrap yard, then after the prepared metal melts to the desired pouring temperature and then pouring into the mold cavity is carried out using the teapot type ladle and allowed to solidify for more than two days. Finally, fettling operation is carried out. Removing the gating and feeding system from the cast part, and further finishing operations according to the customer order is conducted on machine shop.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the data collected and analysis of the input data the following interpretation are drawn:

- Flange roller is the most defective casting product in the case company with 37.5% rejections, to which shrinkage porosity is the main casting defects causing the rejection of the called cast parts.
- Cause and effect diagram, Why-Why analysis, and Pareto charts are quality tools used to define the shrinkage casting defect on the product along with casting simulation for visualizing the filling and solidification related casting defects.

- Poor gating system design, feeding system design, pouring methods, casting design, process control, molding, and venting are the main or potential contributor for the occurrence of casting defect with Risk Priority Number (RPN) of 648, 512, 360, 270, 252, 224, and 210 respectively.
- Attacking the main potential failure i.e. poor gating system design is conducted to minimize filling related casting defects.
- From the existing casting simulation of flange roller casting, the shrinkage defect is on the cast part. Hence, to shift this casting defect to the gating system, two round gating system optimization using ProCAST simulation software with feeding system is conducted and the shrinkage porosity defects are shifted to the gating system.
- The existing gating system has a casting yield of 53.11%. The new gating system has result in a casting yield of 64%. From the two solution, the second solution bring sound casting of the flange roller. The modified gating system result in 10.89% yield improvement with minimized shrinkage casting defects in flange roller cast parts.
- By developing new gating system using silica sand with GFN greater than 60% based on the optimized design of the gating system helps to minimize casting defect and achieve yield improvement.
- From validation results, it is confirmed that, the sand with GFN greater than 60% is used to develop gating system for streamlining the molten metal flow into the mold cavity to minimize filling related casting defects. It is also possible, to use this sand as a facing sand for smooth casting surface finish. As shown in figure xxx, the sprue basin is subjected to sand inclusion GFN between 40% to 60%, while the pouring cup and the sprue has good surface and not subjected to sand inclusion casting defects.

Figure 59: Sand for sprue and pouring cup, good surface finish

- 56.88% molten metal consumption by the existing gating system is reduced to 19 % in new gating system. Hence, the molten material utilization by new gating system layout is reduced by 23.61% as compared to the existing gating system.
- The shrinkage casting defect is shifted to the in-gate of the gating system, and to the neck of the feeding system, which are the removed part during finishing operation, therefore the shrinkage defect is minimized, and sound casting is achieved.

5.2 Recommendations.

Based on the findings of the study the following recommendations are forwarded to the case company:

- The case company must improve data recording methods. Since, casting process involves hundreds of parameters, proper and timely data collections helps in achieving process improvement for defect minimization (optimized casting parameters result in sound casting). Casting process needs continuous improvements for sound casting, this needs a tangible data.
- The case company must ignore an estimated usage of gating system for casting a product. A gating system must be designed for each products of the company, since each product needs a gating process based on the complexity of the products.

- The company must go for standardization. Example, standardization of bill of material, route sheet, man-hours, and machine-hours. This help, to utilize the available resources optimally.
- The company must improve wasting molten metal. The company must balance the required amount of molten metal to fill the mold cavity. The metal melted must be, in balance to the mold cavity in order to minimize wastage of molten metal, thereby losing high costs.
- From the discussion of the research conducted in precision castings foundry different product of the foundry are subjected to casting defects because of casting system design and poor process controls. Continuous training for the foundry operators, proper casting system design, and good combination of optimum process parameters, are the recommended actions by researchers for minimization of the casting defect in casting products of the foundry.
- Application of commercial ProCAST simulation software for predicting the casting defect in the foundry must be used before actual shop floor castings of the products to minimize cost of manufacturing and reworks.

5.3 Further work

The following points are suggested for further study based on the findings of this study:-

- The remaining gating system element including feeding system development using GFN greater than 60% should be studied for further improvement of casting yield. Besides to this using sand having GFN greater than 60% as facing sand for good surface finish of cast parts needs to be studied.
- The impacts of poor process control during complete casting process of parts (Sand preparation, Molding and Mold Assembly, Melting, Pouring, Solidification, and finishing) on the cast parts, and on the company needs to be studied.
- The company faces a molten metal flashes during pouring, between cope and drag of the flask *(below drag as well)* as shown in Figure *60.* To eliminate such problems, development of a plate made from molding sand to be placed inside the mold during assembling drag and cope of flask, should be considered in the future.

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