Adama Science and Technology University

School Of Mechanical Chemical and Materials Engineering

Mechanical Design and Manufacturing Engineering Program

DESIGN & ANALYSIS OF CASTING PROCESS OF MILL ROLLER: A CASE STUDY OF AKAKI BASIC METALS INDUSTRY

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ADAMA, ETHIOPIA

SEPTEMBER, 2018

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitled, **"Design & Analysis of Casting Process of Mill Roller: A Case study of Akaki Basic Metals Industry"** in partial fulfillment of the requirements for the award of the degree of Master of Science in Manufacturing Engineering is an authentic record of my own work carried out December to September, 2018 under the supervision of Dr. B K Singh and Dr. Guteta Kabeta , Program of Mechanical Design and Manufacturing Engineering, Adama science and Technology University, Ethiopia.

The matter embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of our knowledge and belief. This thesis has been submitted for examination with our approval.

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Co-Advisor	Signature	Date

ACKNOWLEDGMENT

First of all I want to thank God for all the extra energy he gave me in the thesis working period. It is no exaggeration to state that without insisting the Almighty God, Jesus Christ, would not have been in a position to finalize successfully accomplished of this thesis paper. So, Glory to him.

I would like to express my heartfelt appreciation and gratitude to my advisor Dr. B K Singh for his invaluable advices and technical supports to strengthen my work. My sincere gratitude goes to my co-advisor Dr. Guteta Kabeta for unreserved effort to shape my thesis as well as for experience and technical guidance throughout the thesis. I have derived a lot of inspiration from them. In fact, this thesis would not have come to its present form, had it not been complemented without their proper follow up in reshaping and organizing. And also I would like to forward my thankfulness to Mr. Abdulmelik Husen for his in depth suggestions and material support given to me.

ABSTRACT

Akaki Basic Metals Industry foundry suffers from poor quality and productivity due to involvement of number of process parameters. The quality characteristics of the mill roller in sand casting has been affected by casting defects caused by in proper process parameter usage and intern affects its proper function that lead to large number of shop floor trials, high rate of rejection and low casting yield. The objective of this research is to design and analyze sand casting process of mill roller. In this research work methods like critical observation, interview, discussion, numerical experimentation and simulation were done at ABMI foundry. Solid modeling of mill roller component with all incorporating gating system was carried out by solidwork software and simulation process was carried out by using proCAST software for the mould filling and solidification analysis to reduce the level and intensities of shrinkage porosities in cast mill roller. Taguchi method of numerical experimentations was carried out for parameter optimization and analysis of variance (ANOVA) using Minitab software. The confirmatory test with the optimal level of casting process parameters were carried out. The casting process parameters of the mill roller were identified by using cause and effect diagram and the parameters were permeability, pouring temperature and, moisture content. Based on the numerical results and their interpretation, the optimal values of the parameters were determined to eliminate the defects. The optimum settings of the selected process parameters of the mill roller was found as permeability 145 (No), pouring temperature 1300℃ and moisture content 2.5%. The percent contribution of each factor were also determined and found as permeability 61.35%, pouring temperature 21.64% and moisture content 2.95%. The improvement in minimizing the casting defects of mill roller was 48.29 percent. Using simulation software, shrinkage porosity was observed in both gating system and roller part.

Key words: parameter optimization, simulation, solidification time, optimum settings, casting defects, analysis of variance.

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LIST OF ABBREVIATIONS

ABMI - Akaki Basic Metals Industry

ANOVA - Analysis of Variance

CAD - Computer Added Design

DOE - Design of Experiment

DOF - Degrees of Freedom

EE - Edge Effect

FD - Feeding Distance

GFN - Sand Grain Fineness Number

MFT - Mold Filling Time

MSE - Mean Square Error

MS - Mean Square

RE - Riser Effect

SN - Signal-to-Noise ratio

SS - Sum of Squares

SST - Total Sum of Squares

LIST OF SYMBOLS

A_L- lateral area of riser,

A_t - top cross-sectional area of riser

A_e - exit area of riser

A- Cross-sectional area of gating system

A_{Sexit} -Sprue exist area

A_{Stop} - Sprue top area

A_C- surface area of casting

A_r - surface area of riser

A_{Sig} - surface area of ingate

A - Total surface area of riser

CS(r) - mold constants of riser

CS(c) - mold constants of casting

d_t - top diameter of riser

d_e - exit diameter of riser

d_{top} -top sprue diameter

d_{exit} -exit sprue diameter

dr_{top},- Top riser diameters

dr_{exit} - exit riser diameters

dn - riser neck diameter

fi - amount of sand retained on ith sieve

g - Acceleration due to gravity

H - Height of metal head on the cope side

H_n - riser neck height respectively

H_f - Heat of fusion of metal

h - Heat transfer coefficient at mold-metal

hc - Convection heat transfer coefficient

h_i - height of the ingate section

h_{sb} - Height of the sprue base

h_S - Sprue height

h_{pc} - Pouring cup height

H_{ic} - Grooved height of the ingate section

K_m - Thermal conductivity of mold materials

K_s - Thermal conductivity of solid materials

Mi - Multiplying coefficient for the i^{th} sieve

Mr - Modulus of the riser

Mc - Modulus of the casting

N - Number of trials of each experiment

Q - Volumetric flow rate

Q_{ave} - Average flow rate of casting

Q_1 - Volume flow rate at the sprue inlet cross-section

A_1- entrance sprue cross-sectional area

V_1- linear velocity of flow at sprue entrance

Q_2 -Volume flow rate at the sprue exit cross-section

A_2 - exit sprue cross-sectional area

V_2 - linear velocity of flow at sprue exit

Q_3 -Volume flow rate at the ingate inlet and out let cross-section

A_3 - actual ingate inlet and exit areas

V_3 - velocity of metal at ingate inlet and outlet section

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

Sand Casting is a manufacturing process by which a liquid material is usually poured into a mold, which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting is a metal part formed by pouring molten metal into a sand mold. The mold is comprised of two halves that, when mated together, form a cavity into which the molten metal is poured. If an internal cavity is required in the casting, a core is placed inside the mold cavity. In sand casting process, after the metal solidifies, the mold is broken, the cores removed and the part is readied for finishing operations. The sand is then remolded and used again [1].

During sand casting of grey cast iron, whenever the molten grey cast iron is allowed to cool in the atmosphere its carbon content comes out of solution forming flakes of graphite, which spreads, through the ferrite/pearlite matrix and the flake graphite iron is formed. In general the grey cast iron finds its application in making of machine tool bodies, automotive cylinder blocks, heads, housings, fly-wheels, pipes and pipe fittings and agricultural implements [2] The whole process of producing castings can be summarized in to five stages [3]; (i) Pattern making, (ii) Molding and core making, (iii Melting and casting, (IV) Fettling and (v) Testing and inspection.

Sand Casting is a manufacturing process for making complex shapes of metal materials in mass production. There are two main consecutive stages, filling process and solidification process, in casting production. In filling process gating system composed of pouring cup, runner, sprue, sprue well and ingate, is designed to guide liquid metal filling. Riser system is used to compensate shrinkage caused by casting solidification [4].

While casting of grey cast iron there are several factors that affect their quality. It is unavoidable that many different defects occur in sand casting process, such as shrinkage porosity and incomplete filling. Shrinkage Porosity may be the most persistent phenomena in casting, and it is hard to be eliminated completely [5].

Porosity is harmful to the ductility of the casting and its surface finish. Porosity in castings is due to bubbles being trapped during solidification. It may be caused by shrinkage, or gases, or both. There are many factors contribute to the development of porosity such as the entrapped air during filling, blowholes from unvented cores, dissolved gases from melting, etc. Because liquid metals have much greater solubility for gases than do solid metals, when a metal begins to solidify, the dissolved gases are expelled from the solution. It will cause microporisty or accumulate in regions of existing porosity. There are different types of defects produced in sand casting. A high proportion of casting defects are caused due to evolution of gases [5].

The variety of defects can be generated by equipment malfunction, process variation, and an improper process operation. Therefore, manufacturing system variables that affect product quality are related to operators' skills, capability of machines, human actions during the production process, and workplace environment. In order to improve the quality and to reduce the defects, various engineering tools and techniques are employed [6].

Taguchi's method is one of the most popular tools for development of engineering products. It helps in improving the quality of the product by making simple changes in the methods by which the engineers accomplish their design tasks. Taguchi offers a systematic approach for optimization of various parameters with regard to performance, quality and cost. Design of experiment is a systematic approach to investigate a process. A series of tests are performed by making changes to the inputs of the processes and their effect on the output of the process is analyzed. This experimentation aims to determine the most significant, controllable design parameters so that they can be optimized to make the system robust to noise [2].

With the generalization of CAD 3D modeling and the increase of computing performance, casting simulation software has reached a state where a relevant input for the design of a component can be given to the process engineers. Gating systems, overflows, venting channels can be optimized using numerical simulation. Solidification related defects like hot spots can also be predicted taking into account cooling channels [7].

The use of computational methods and numerical simulations in sand casting has become a powerful tool to analyze mold filling, solidification, and cooling, and to envisage the location and type of internal defects. These simulation methods allow modern foundries to shift from conventional ''trial-and-error'' to ''proof-of-concept'' approach in product development paradigm [8].

ProCAST is a three dimensional solidification package developed to perform numerical simulation of molten metal flow and solidification phenomena in various casting processes, it is very helpful for foundry applications to visualize and predict the casting results so as to provide guidelines for improving product also mold design to get the desired casting qualities. Conventional sand casting is not a precision process and requires machining and surface finishing process after casting. However, advanced high technology sand casting process enables this method to produce higher precision cast products with better surface finishing that reduces the cost of machining and surface finishing processes. This was enhancing the capability of sand casting to produce almost exact shape products and improve its qualities [9].

1.2 Statement of the problem

Manufacturing of defect-free components at low cost and high productivity is important for the casting industry today. Foundry suffers from weak quality and productivity due to a huge number of process parameters, lower automation and shortage of skilled workers. Defect free products are demanded in market but foundry finds to meet the requirements. The major challenges that Akaki Basic Metal industry faces are large number of shop floor trials, high rate of rejection and low casting yield. This is due to the fact that appropriate efforts have not been done so far on the control of sand casting process parameters of mill roller rather on mass production. Unless proper optimization techniques are taken on control of variables, presences of casting imperfections exist that pose many challenges to foundry experts. Due to that, the foundry industry losing a huge amount of resources spent from product and casting design to final production and this affect the economic growth of the factory. These can be overcome by applying Taguchi Method of design of experiments and casting simulation technique which is to be an important tool for continuous and rapid improvements in quality. The Taguchi Method and Casting simulation technique is a numerical experimental technique that helps to investigate the best combinations of process parameters, changing quantities, levels and combinations in order to obtain results statically reliable.

1.3 Objective of the study

1.3.1 General Objective

The general objective of this study is to design and analyze sand casting process of mill roller manufactured at Akaki Basic Metals Industry.

1.3.2 Specific objectives

- To design gating and risering system of mill roller.
- To analyze casting defects developed during mill roller castings.
- To identify parameters that has significant impacts on casting defects.
- To select optimum levels of the process parameters.
- To develop a 3D model of Mill roller and gating system pattern by Solidwork software.
- To analyze filling and solidification related defects using proCAST software.

1.4 Research Questions

Research question is the question form of the specific objectives. Therefore, the followings were the research question identified for the study in line with the above specific objectives.

- What are the types of defects developed during mill roller castings?
- Which parameters are has the most significant impact on casting defects?
- Which method employed to analysis defects developed during mill roller castings?
- What are the optimum levels of the process parameters?

1.5 Significance of the study

The significance of this study is for ABMI foundry to achieve high quality castings and to reduce the rejection rate of castings. Taguchi's approach of quality engineering is applied to solve casting defect problems of mill roller. Taguchi's method of numerical experiment is implemented to reduce the casting defects developed during the casting process. Generally, Optimization of casting process benefit these industries to minimize casting defects, reduce risk, enhance their productivity, earn industrial profit and economic growth. It gives customers' satisfaction due to the fact that high quality and defects free castings can be produced. It is also best for other foundry manufacturer's industries.

1.6 Limitations of the study

- ✓ A problem of time to collect all necessary data from foundry of the industry.
- ✓ Some respondents were involuntary to give available information.
- ✓ Limited number of laboratories found in ABMI foundry.
- ✓ Lack of thermo-physical measuring apparatus for measuring the mold cavity and an assumption has made for the completion of the study.
- ✓ ProCAST software cannot predict all types of defects that may occur in a casting, such as processing defects and human error.
- ✓ ProCAST software cannot predict Additional chemical elements added to the molten metal.

1.7 Scope of the study

The scope of this study is to design and analyze sand casting process of mill roller. Taguchi's approach of quality engineering and casting simulation technique is to minimize the rejection rate of sand casting mill roller due to defects. It is also intended to analyze casting defects developed during the mill roller casting process produced by sand casting of the foundry at Akaki Basic Metals Industry. To identify parameters that has significant impacts on the mill roller casting defects and to analyze filling and solidification related defects using proCAST software.

1.8 Organization of the thesis

This thesis is organized as follow. Chapter 1 discusses the background, statement of the problem, objective, research questions, significance of the study, limitations of the study and scope of the study. Chapter two presents a literature review that discusses the basic and fundamental concepts related to casting defects, gating system design, metal flow conditions, metal melting, pouring and design of experiments and software applications. Chapter 3 discusses the materials and methods employed during the research work. Chapter 4 discusses the data analysis and the case study of the company. The data collected from the industry foundry is analyzed which would be used in determining of the optimum conditions of process parameters of mill roller castings for ABMI industry. In chapter five results were discussed and causes of defects occurred in mill roller castings were also identified for parameter optimization. Based on the numerical result, design of experiment method has been implemented for ABMI foundry. In the last chapter conclusion, recommendation and future work areas have been presented.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Metal Casting

Metal casting is a versatile manufacturing process in which liquefied metal is poured into previously prepared mould cavity and allowed to solidify. Subsequently the product is taken out of mould cavity, trimmed and cleaned to shape. Casting can produce products from few grams to several hundred tons and from simple shapes like watch cases to most complex parts like engine blocks. It is a near net shape manufacturing process involving less or no further operations. Almost any metal or alloy which can be easily melted is castable [10].

Casting has many process variations depending upon the material, the type of pattern, mould and the pouring technique like sand casting, investment casting, die casting, squeeze casting and lost foam casting. Sand casting is the most widely used process which can be used to produce intricate parts in almost every metal that can be melted [11].

2.2 Sand casting

Sand casting is an important manufacturing process in industries today. It is an economic method for mass production of complex metal products. However, conventional method of manufacturing sand casting pattern has not been able to meet customer satisfaction due to its difficulty of producing complex and intricate parts, either in wood or metal patterns. The wood pattern fails to produce thin parts while the metal pattern fails to produce complex shapes and contour parts [12].

2.2.1 Sand Casting Processes

Sand casting is widely used for centuries because of the simplicity of the process. The sand casting process involves the following basic steps: (a) place a wooden or metallic pattern in sand to create a mold, (b) fit in the pattern and sand in a gating system, (c) remove the pattern, (d) fill the mold cavity with molten metal, (e) allow the metal to cool, and (f) break the sand mold and remove the casting. The sand casting process is usually economical for small batch size production. The quality of the sand casting depends on the quality and uniformity of green sand material that is used for making the mold. Figure 2.2 schematically shows a two-part sand mold, also referred to as a cope-and-drag sand mold. The molten metal is poured through the pouring cup and it fills the mold cavity after passing through down sprue, runner and gate. The core refers to loose pieces which are placed inside the mold cavity to create internal holes or open section. The riser serves as a reservoir of excess molten metal that facilitates additional filling of mold cavity to compensate for volumetric shrinkage during solidification. Sand castings process provides several advantages. It can be employed for all types of metal. The tooling cost is low and can be used to cast very complex shapes. However sand castings offer poor dimensional accuracy and surface finish [13].

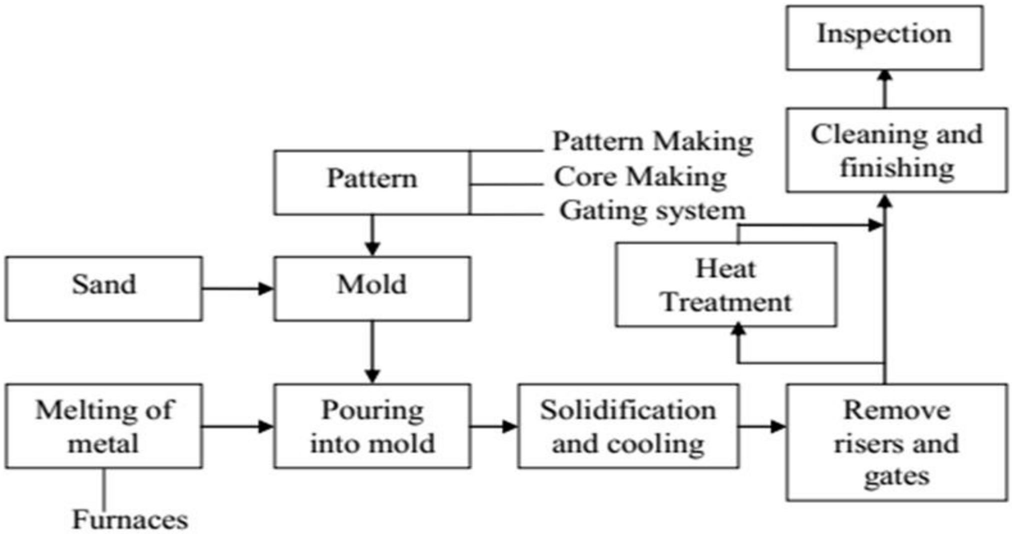

Figure 2.1 Production steps in a typical sand casting process [13].

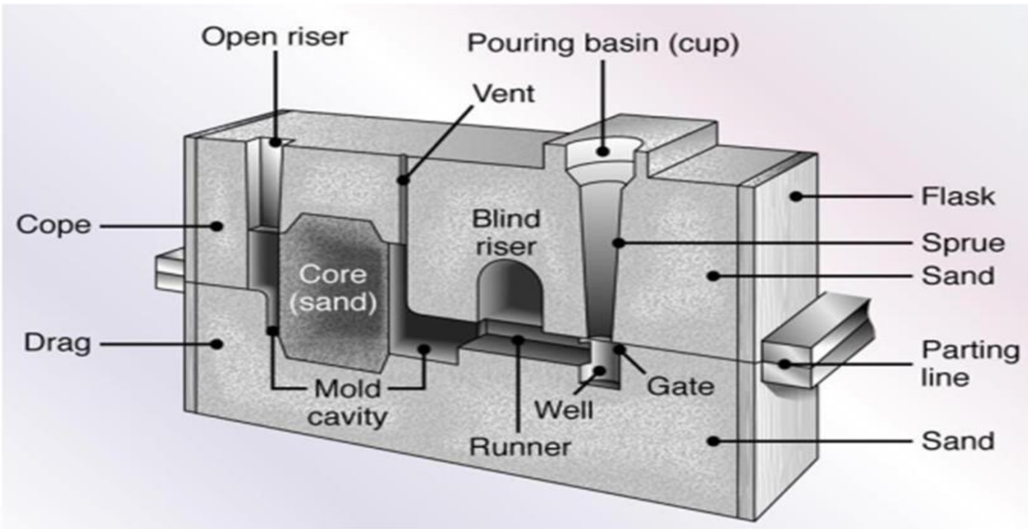

Figure 2.2 Schematic illustration of a sand mold [13].

2.2.2 Solidification

Solidification, also known as freezing, is a phase change of matter that results in the production of solid. Solidification normally begins on the surface of the casting and moves inward toward the center of the casting or toward the source of feed metal. Solidification occurs in two steps: nucleation and crystal growth. In the nucleation stage solid particles form with in the liquid. When these particles form their internal energy is lower than the surrounded liquid, which creates an energy interface between the two. The formation of the surface at this interface requires energy, so as nucleation occurs the material actually undercools, that is it cools below its freezing temperature, because of the extra energy required to form the interface surfaces. It then heats back up to its freezing temperature, for the crystal growth stage. All of the nucleation represents a crystal, which grows as the heat of fusion is extracted from the liquid until there is no liquid left. The direction, rate, and type of growth can be controlled to maximize the properties of the casting. Directional solidification is when the material solidifies at one end and proceeds to solidify to the other end; this is the most ideal type of grain growth because it allows liquid material to compensate for shrinkage [12].

2.2.3 Sand casting process design

The principles of successful casting design involve a systematic blend of experience and engineering basics to allow the creation of a successful casting, from inception through production. The typical sand casting process design consists of the following steps [13].

Sand Selection: Several factors are important in the selection of sand for molds, and it involves certain tradeoffs with respect to properties. Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability. Good permeability of molds and cores allows gases and steam evolved during the casting to escape easily. The mold has should have good collapsibility to allow for the casting to shrink while cooling and, thus, to avoid defects in the casting, such as hot tearing and cracking.

Parting line: Parting line is the line or plane separating the upper and the lower halves of molds. In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the parting line should be at the corners or edges of castings rather than on flat surfaces in the middle of the casting. It should be placed as low as possible for less dense metals and located at around mid-height for denser metals.

Pattern design: The pattern is a replica of the object to be cast, used to prepare the cavity into which molten material will be poured during the casting process. Patterns used in sand casting may be made of wood, metal, plastic or other materials. Patterns are made to exacting standards of construction, so that they can last for a reasonable length of time. The mold is made by packing some readily formed aggregate material, such as molding sand, around the pattern. When the pattern is withdrawn, its imprint provides the mold cavity, which is ultimately filled with metal to become the casting.

During the design process of pattern, some considerations should be taken. For example, the pattern needs to incorporate contraction allowances, which are suitable allowances for shrinkage. And also it needs to incorporate suitable allowances for draft. If the casting is to be hollow, as in the case of pipe fittings, additional patterns, referred to as cores, and are used to form these cavities.

Core design: A core is a device used in casting and moulding processes to produce internal cavities and reentrant angles (an interior angle that is greater than 180°). The core is normally a disposable item that is destroyed to get it out of the piece. Cores are forms, usually made of sand, which are placed into a mold cavity to form the interior surfaces of castings. Thus the void space between the core and mold cavity surface is what eventually the casting becomes.

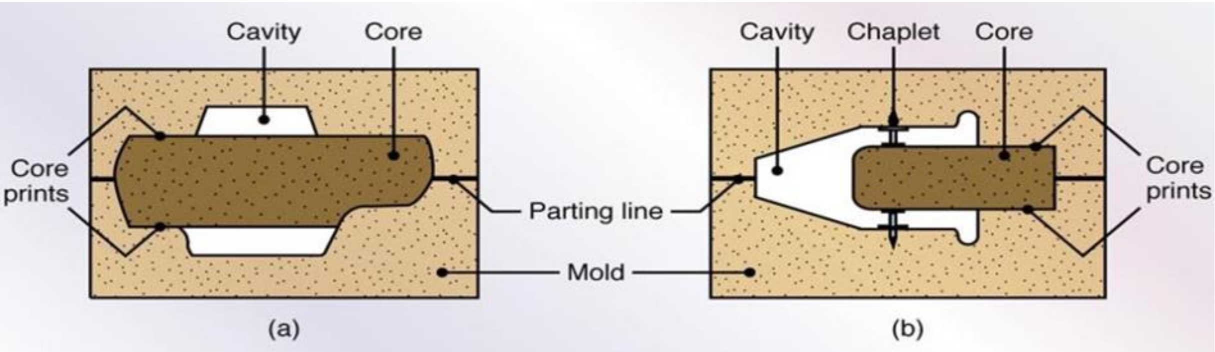

Figure 2.3 core design of sand casting [15].

2.2.4 General properties of molding sand

The basic properties required in molding sand and core sand are adhesiveness, cohesiveness, collapsibility, flowability, dry strength, green strength, permeability, refractoriness described as under [14].

Adhesiveness: Adhesiveness is a property of molding sand to get the stick or adhere to foreign material such sticking of molding sand with the inner wall of molding box.

Cohesiveness: Cohesiveness is property of molding sand by virtue which the sand grain particles interact and attract each other within the molding sand. Thus, the binding capability of the molding sand gets enhanced to increase the green, dry and hot strength property of molding and core sand.

Collapsibility: After the molten metal in the mould gets solidified, the sand mould must be collapsible so that free contraction of the metal occurs and this would naturally avoid the tearing or cracking of the contracting metal. In absence of collapsibility property the contraction of the metal is hindered by the mold and thus results in tears and cracks in the casting. This property is highly required in cores.

Dry strength: As soon as the molten metal is poured into the mould, the moisture in the sand layer adjacent to the hot metal gets evaporated and this dry sand layer must have sufficient strength to its shape in order to avoid erosion of mould wall during the flow of molten metal.

The dry strength also prevents the enlargement of mould cavity cause by the metallostatic pressure of the liquid metal.

Flowability or plasticity: Flowability or plasticity is the ability of the sand to get compacted and behave like a fluid. It will flow uniformly to all portions of pattern when rammed and distribute the ramming pressure evenly all around in all directions. Generally sand particles resist moving around corners or projections. In general, flowability increases with decrease in green strength and vice versa. Flowability increases with decrease in grain size of sand. The flowability also varies with moisture and clay content in sand.

Green strength: The green sand after water has been mixed into it, must have sufficient strength and toughness to permit the making and handling of the mould. For this, the sand grains must be adhesive, i.e. they must be capable of attaching themselves to another body and. therefore, and sand grains having high adhesiveness will cling to the sides of the molding box. Also, the sand grains must have the property known as cohesiveness i.e. ability of the sand grains to stick to one another. By virtue of this property, the pattern can be taken out from the mould without breaking the mould and also erosion of mould wall surfaces does not occur during the flow of molten metal. The green strength also depends upon the grain shape and size, amount and type of clay and the moisture content.

Permeability: Permeability is also termed as porosity of the molding sand in order to allow the escape of any air, gases or moisture present or generated in the mould when the molten metal is poured into it. All these gaseous generated during pouring and solidification process must escape otherwise the casting becomes defective. Permeability is a function of grain size, grain shape, and moisture and clay contents in the molding sand. The extent of ramming of the sand directly affects the permeability of the mould. Permeability of mold can be further increased by venting using vent rods.

Refractoriness: Refractoriness is defined as the ability of molding sand to withstand high temperatures without breaking down or fusing thus facilitating to get sound casting. It is a highly important characteristic of molding sands. Refractoriness can only be increased to a limited extent. Molding sand with poor refractoriness may burn on to the casting surface and no smooth casting surface can be obtained. The degree of refractoriness depends on the SiO2 i.e. quartz content, and the shape and grain size of the particle. The higher the SiO2 content and the rougher the grain volumetric composition the higher is the refractoriness of the molding sand and core sand. Refractoriness is measured by the sinter point of the sand rather than its melting point.

2.2.5 Sand Casting defects

Casting defects are unusually not by accidents, they occur because some step in manufacturing cycle does not get properly controlled and somewhere something goes wrong practice in one or more of the basic operations involved in the casting process as in the equipment used, or by the design of the part. It also mentioned that casting defects are because of improper pattern/tool design or lack of allowances, improper mould and core constituents, improper melting practice, improper pouring practice, because of molding and core making materials, improper gating - risering system along with lack of feed-aids, improper metal composition, inadequate melting temp and rate of pouring, and unskilled post melting treatment like shakeout, fettling [13].

During the metal casting process, various defects were developing. They are illustrated in figure 2.4 below. It is important to improve the casting quality by eliminating or minimizing the effects caused by those defects.

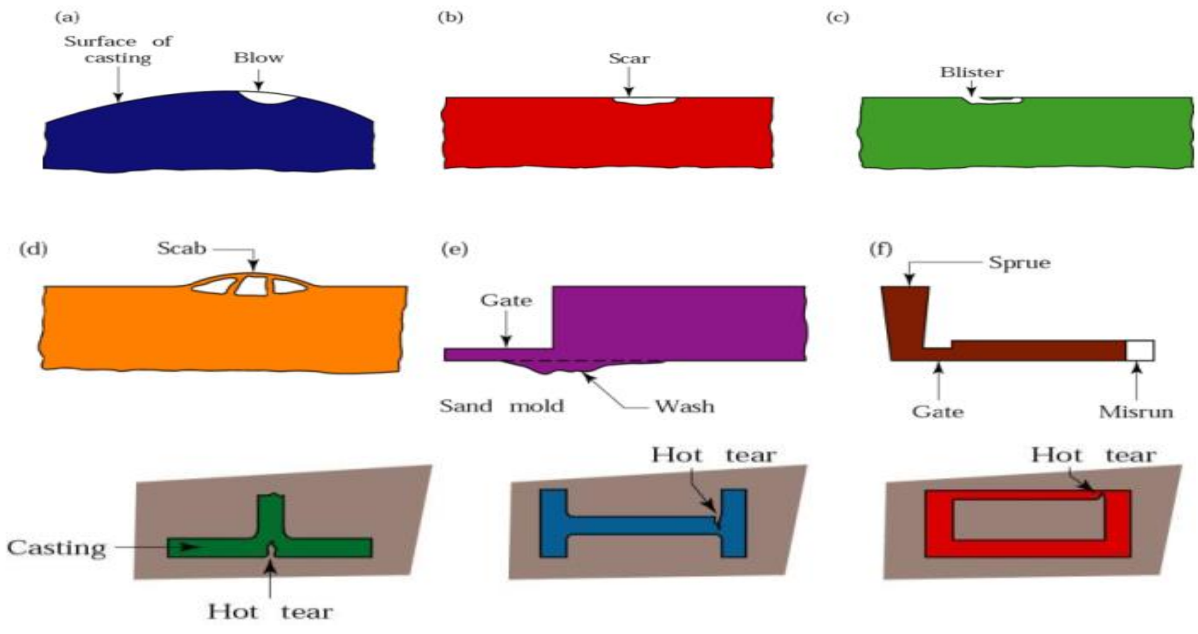

Figure 2.4 some defects in sand casting [16]

2.2.6 Factors affecting Castability of ferrous alloy

The ability of the melt to fill up the mould large or small, simple or complex depends on many factors. Some of the factors are (i) fluidity of the molten metal in which cast iron melt has moderate fluidity and fluidity decreases slowly with temperature, that is, grey cast iron have higher fluidity than other cast iron. Higher the carbon level lower is the melting point and higher is the fluidity.

(ii) Solidification shrinkage-volume shrinkage is very high for grey cast irons but quite small for other cast iron and non-ferrous alloys. The size of the feeders (risers) has to be large enough. As a result, yield of the casting can be quite high – 80 % (iii) Melting and pouring temperature-melting temperature is directly linked with cost of melting, in terms of energy cost and cost of wear and loss of refractories in the furnace[18] .

2.2.7 Effect of alloying elements

Carbon is more effective in reducing solidification shrinkage and silicon is more effective in preventing thin section from becoming hard. The presence of high carbon and silicon in cast irons, usually above 2%, they possess lower melting temperature, better fluidity and lesser reactivity with molding materials as compared to steel. Some of the alloying elements which have significant influence are Manganese (improves hardenability, ductility and wear resistance), Silicon (decreases the solubility of carbon in liquid and solid solutions and encourages graphitization), Chromium (improves hardenability, strength and wear resistance), Molybdenum (increases hardenability and strength particularly at high temperatures and under dynamic conditions) and Phosphorus (reduces the solubility of carbon and has insignificant effect on graphitization) [19].

2.2.8 Gating system

A network of channels in the mold that deliver molten metal from a pouring vessel to the mold cavity, The main objective of a gating system is to lead clean molten metal poured from ladle to the casting cavity, ensuring smooth, uniform and complete filling. Clean metal implies preventing the entry of slag and inclusions into the mould cavity, and minimizing surface turbulence. Smooth filling implies minimizing bulk turbulence. Uniform filling implies that all portions of the casting fill in a controlled manner, usually at the same time. Complete filling implies leading molten metal to thin and end sections with minimum resistance [13].

Metals can be poured in to mold using three common methods namely (i) bottom gates allows easy flow of metal into the mold that reducing erosion of the mold and core surfaces results in quiet, smooth flow and reducing the danger of entrapped air. This gating type produces with a minimum of turbulence in the metal (ii) top gate which is limited by the ability of the mold to withstand erosion, because the molten metal is usually poured through an open-top system. Producing favorable temperature gradients but excessive mold erosion whereas (iii) parting line gates which are simple to construct and molten metal drops in the mold to fill the drag part of the casting and this causes erosion or washing of the mold. Gating directly into the casting produces hot spots, because all of the metal enters the casting through the gates and the sand near the gates becomes very hot and retards cooling of the metal. Unless risers are provided for feeding these portions of the casting with molten metal, cavities or shrinkage defects can be formed [18].

2.2.9 Elements of gating system

It usually comprises of, a Pouring Cup (a cavity that receives melt from the pouring vessel), a Sprue (a vertical portion of the gating system), Runners (horizontal portion of the gating system) and Gates (channels that controls entrance to mold cavity). Other features like Wells (sprue well and extension wells) and Extensions (runner and flash) are also common features that make up a gating system. [20]

1) Types of gating system

The gating system can be classified in to pressurized and unpressurized system based on the choice of the location of the flow-controlling constriction, or choke that can be determine the ultimate flow rate for the gating system. This involves the determination of a desired gating ratio, that is, the relative cross-sectional areas of the sprue, runner and gates. This ratio numerically expressed in the order sprue: runner: gate that defines whether a gating system is increasing in area (unpressurized) or constricting (pressurized) [18]

Unpressurized system has the advantage of reducing metal velocity in the gating system as it approaches and enters the casting which results in laminar (or less turbulent) flow, so recommended for alloys that are highly sensitive to oxide and dross formation. This gating system helps displacing non-metallic inclusions into the runner extension, floating slag and minimizing spurting of the metal from the gate into the mould cavity and typical gating ratio can be 1:2:2, 1:2:4, 1:3:3 or 1:4:4 [18, 19].

Pressurized gating systems have the advantage of reduced size and weight for a given casting, thus increasing mold yield. In this system, ingates serve as the choke and maintains a back pressure and causes the entire gating system to become pressurized. Pressurized system restricts the rate of metal flow into the mould cavity and provides an opportunity for the slag to float at the top of the sprue or in the pouring basin. The disadvantage of this system is that, by design, stream velocities are highest at the gates just as the metal enters the casting. A typical gating can be 4:3:2 [18, 19].

2) **Design of gating system elements**

The gating system can be designed with the assumption that same quantity of metal is passing per unit time through each of the elements. The dimensions of the gating system can be designed using laws of fluid dynamics namely Continuity law and Bernoulli's theorem. The volume flow rate of metal is considered uniform throughout a system and determined from the continuity law using the following Equation [18, 19].

$Q = A1V1 = A2V2 = A3V3 = AnVn \cdots\cdots\cdots \text{(2.1)}$

Where, Q-Volume flow rate of molten (volume of metal passing per unit time), A-Cross-sectional area of the passage, and V- linear velocity of flow, and A_n and V_n –are area of passage and velocity of flow at n-location of the passages. The total energy of a flowing stream is the sum of all the energies without consideration of losses in the passages and this can be calculated using the Bernoulli's theorem using the following formula [11].

$$\frac{V^2{}_1}{2g} + h_1 + \frac{P_1}{\rho_f} = \frac{V^2{}_2}{2g} + h_2 + \frac{P_2}{\rho_f} = \frac{V^2{}_n}{2g} + h_n + \frac{P_n}{\rho_f} \cdots\cdots\cdots \text{(2.2)}$$

Where, h-height of fluid column above the datum plane, P- static pressure of fluid, ρ_f - density of fluid, Vn- Pn and h_n - are linear velocity, static pressure and height of fluid at any location of the passages respectively.

A) Design of pouring basin

Pouring cup is the entrance through which molten metal is introduced into the cavity and designed by considering the following aspects [20]:

(i) the basin itself has to be filled up quickly in order to reduce the pouring head

(ii) melt should be poured from the blind end of the basin so that the fall of the stream is arrested, and bubbles and dross may have chance to float up to the surface

(iii) exit of the basin should be larger than the entrance of the sprue to avoid air aspiration at the basin/sprue connecting location and

(iv) Pouring basin with a round bottom may cause tendency of the metal to rotate, forming a vortex and hence aspirating air.

B) **Design of sprue**

In casting, a sprue is the passage through which a molten material is introduced into a mold, and the term also refers to the excess material which solidifies in the sprue passage. In sand casting, the sprue is formed by a dowel, which is removed from the sand to make the hole into which the metal is poured [16].

Metal is poured from a ladle into a pouring basin and after passing over the dam, the metal enters the sprue. The liquid metal accelerates due to gravity as it falls through the sprue. The cross sectional area of the metal stream would be reduced due to gravitational acceleration and continuity of material. A constant diameter sprue may exposed free surface area of the metal stream that leads to aspiration of gas from the permeable sand mold, which would cause oxidation and hence contamination of the incoming metal and solidification starts [5].

C) Design of ingate

Gates are the inlets into the mold cavity. The gates can be no thicker than the casting section to which they are attached. Even more it usually is best to have the gates slightly thinner than the casting section. If the gating system is not completely filled during the entire pour, it will not function correctly, and defective castings can result [13].

Ingate area is the smallest area in the feeding channels which controls the flow rate of metal into the mold cavity and in turn controls the pouring time. The total ingate areas of the system in castings are determined using following formula [5],

$$\sum A_i = \frac{W_g}{\mu \times \rho_m \times t_p \times \sqrt{2gh}}\ cm^2 \quad \text{(2.3)}$$

Where, Ai-total ingate area, W_g - Gross weight of casting (Kg), ρm - density of metal H-effective height of metal head in the cope side, μ- efficiency factor or nozzle coefficient which is a function of gating system employed, g - acceleration due to gravity, t_p - pouring time in seconds

D) **Gating system ratios**

The term gating ratio is used to describe the relative cross-sectional areas of the components of a gating system. It is defined as the ratio of sprue area to the total runner area to the total gate area [19].

In gating system the shape and dimensions of the passages are the most important characteristics which determine the rate and type of flow and the position at which the metal enters the mould cavity. The dimensional characteristics of any gating system areas are expressed in term of gating ratio by the following relations [17],

$$Sprue(exit)area: Runner\ area: total\ ingate\ areas$$

E) **Design of sprue sectional area**

While a casting is made the average flow rate of the casting for individual castings can be determined by dividing the casting weight with the measured filling time and also the mold filling time can be estimated from the ratio of volume of the mold cavity to the average volumetric flow rate using the following formulae respectively [22],

$$Q_{ave} = \frac{W_g}{t_f}\ and\ MFT = \frac{V}{Q_v} \quad \text{(2.4)}$$

Where, Q_{ave}– average flow rate of casting, W_g - Gross weight of casting, and t_f - measured filling time, MFT - mold filling time, V-volume of mold cavity, and Q_v- volumetric flow rate

The sprue entrance and exit areas, the sprue and the pouring cup heights can be also related using the following Equation, [22],

$$A_{Stop} = A_{Sexit}\left(\sqrt{1+\frac{h_s}{h_p}}\right) \qquad (2.5)$$

Where, A_{Stop} - sprue entrance area, A_{Sexit} - sprue exit area, h_s - height of sprue and h_p- height of pouring cup

2.2.10 Riser design

Riser is a source of extra metal which flows from riser to mold cavity to compensate for shrinkage which takes place in the casting when it starts solidifying. Without a riser heavier parts of the casting will have shrinkage defects, either on the surface or internally [19].

Risers are used to compensate for liquid shrinkage and solidification shrinkage. But it only works if the riser cools after the rest of the casting. Chvorinov's rule states that the solidification time t of molten metal is related to the constant C (which depends on the thermal properties of the mold and the material) and the local volume (V) and surface area (A) of the material, according to the following Equation, [13]

$$t = C \times \left(\frac{V}{A}\right)^2 \qquad (2.6)$$

Therefore, to ensure that the casting solidifies before the riser, the ratio of the volume to the surface area of the riser should be greater than that of the casting. The riser must satisfy two requirements: it must be large enough so that it solidifies after the casting (i.e. satisfies Chvorinov’s rule) and it must contain a sufficient volume of metal to supply the shrinkage contraction which occurs on cooling from the casting temperature to the completion of solidification.

Hence the casting should be designed to produce directional solidification which sweeps from the extremities of the mold cavity toward the riser. In this way, the riser can feed molten metal continuously and will compensate for the solidification shrinkage of the entire mold cavity. If this type of solidification is not possible, multiple risers may be necessary with various sections of the casting solidifying toward their respective risers [12].

A) Riser size

Currently riser size can be calculated with the aid of modulus. Modulus equals to the ratio between its volume and its surface area. The modulus method compares the modulus of the riser and that of the casting or section to be fed. Most literatures say the modulus of the riser should be 20% larger than that of section being fed. This method can also be used to determine the size of riser neck. It is commonly agreed that the modulus of the riser neck should be 10% larger than that of the section being fed [13].

B) Riser shape

Because it is required that the ratio of the volume to the surface area of the riser should be greater than that of the casting, the riser's geometric shape should be adjusted to have a larger ratio. For a given volume of molten cast iron, the shape selected should have the least possible amount of surface area [13].

C) Number of risers

The number of risers employed depends on the shape of the casting and the feeding distance of the metal. The number of risers required and their volume can be reduced by using external chills or by using cored holes in heavy sections. The mold is made in such a way that directional solidification is promoted, that is, solidification starting in thin sections, proceeds towards the riser. Isolated heavy sections require risers to produce sound metal in those locations. A proper taper in the casting or padding can promote directional solidification towards the riser and helps in producing defect free casting [23].

D) Riser location

Risers are usually placed over thick section of the casting to provide the feed metal or to the casting last to solidity. A thicker section of the casting acts as a reservoir for feeding the thinner sections which solidify first and thicker sections are fed by the risers. Because feeding from the risers depends upon gravity they are usually located at the top of the mould. Such open risers also serve as collectors for nonmetallic inclusions which float up to the surface apart from feeding the casting to compensate for the shrinkage [5].

E) Feeding distance

The distance a riser can deliver feed metal into the casting section to which it is attached is called its feeding distance. If the feeding distance of one riser exceeds its limit, it will become ineffective and shrinkage may be produced. Feeding distance of risers is determined by the alloy being poured and by the thickness of the section being fed. For grey cast iron castings, the theoretical feeding distance of a hot riser was determined using the following Equation formula [13].

$$FD = 2 \times T \quad \cdots\cdots (2.7)$$

Where, FD is the feeding distance and T is the thickness of the section being fed

3) Requirements of gating system

There are many factors affecting the design of an ideal gating system. For example, the gating system should be designed to allow the molten metal flow through with the least amount of turbulence. It is a better design of the gating system that it can be removed easily from the casting after filling. The gating system should be designed in such a way to promote the directional solidification. After meeting other requirements of gating system, it will also need lower yield [12].

2.3 Taguchi Methods in Quality Engineering

Recently, Taguchi methods have become very popular among industries worldwide. Many academic research papers and industrial application reports have been published under the title “Taguchi methods”. In fact, the so called “Taguchi method” is collective term. It consists of systems of experiment design, quality engineering, business data analysis, and divisional evaluation system and pattern recognition [24].

There are a lot of literatures written for optimization of manufacturing process parameters using Taguchi Method. Some of these are:

Rasik and Upadhye et al. [25] Discussed to optimize the sand casting process parameters of the castings manufactured in iron foundry by maximizing the signal to noise ratios and minimizing the noise factors using Taguchi method. The process parameters considered are moisture, sand particle size, green compression strength, mould hardness, permeability, pouring temperature, pouring time and pressure test. The results indicated that the selected process parameters significantly affect the casting defects in the foundry. The improvement expected in reduction of casting defects is found to be 37.66 percent. The optimum conditions for the factors computed are Moisture (%) – Level 1 – Minimum 3.5, Green compression strength (g/cm2) – Level 1 – Minimum 900, Permeability – Level 2 – Minimum 185 and Pouring temperature (deg. Celsius) – Level 3 – Maximum 1420. The improvement expected in minimizing the variation is 37.66 percent which means reduction of casting defects from present 6.16 percent to 3.84 percent of the total castings produced in the foundry.

Uday A, Dabade et al. [26] analyzed the optimized levels of selected process parameters obtained by Taguchi methods are: moisture content (A): 4.7 %, green compression strength (B): 1400gm/cm2, permeability number (C): 140 and mould hardness number (D): 85. With Taguchi optimization method the % rejection of castings due to sand related defects is reduced from 10 % to a maximum up to 3.59 %. Design of experiments method such as Taguchi method can be efficiently applied for deciding the optimum settings of process parameters to have minimum rejection due to defects for a new casting as well as for analysis of defects in existing casting.

Hiren, Khalasi et al. [27]. this research work present the design of experiment based approach which is adopted to obtain an optimal setting of moisture content, grain particle size and temperature of pouring metal related parameters of green sand casting in susha founders.

The casting parameters identified for green sand casting process are moisture content, green strength, mould hardness, permeability, sand particle size, pouring temperature ramming pressure, cooling time. For defect analysis, the possible causes are grouped into design, material and process parameters. The effect of suspected cause parameters on casting quality is ascertained through simulation. Based on the results and their interpretation, the optimal values of the parameters are determined to eliminate the defects.

Satish, Kumar et al. [28] analyses different parameters of pressure die casting to minimize the casting defects. Pressure die casting is usually applied for casting of aluminum alloys. Good surface finish with required tolerances and dimensional accuracy can be achieved by optimization of controllable process parameters such as solidification time, molten temperature, filling time, and injection pressure and plunger velocity. Overall 2.352% reduction in defects has been observed with the help of suggested optimum process parameters.

G.O Verrana et al. [29] discusses the application of a design of experiments (DOE) experimental method for analyzing the influence of three injection parameters (slow shot, fast shot and upset pressure) on the internal quality of die casting SAE 305 alloy parts. The quality assessment of the die casting parts was based on density measurements and qualitative image analysis. Results were evaluated by means of variance analysis, which assessed how the variation in the three different injection parameters influenced the integrity of the components. Saravan, kumar et al. [30] in this paper the casting defects such as, Shrinkage, sand drop, sand blow holes, scabs, pinholes are minimized by using Taquchi optimization technique. The parameters considered are moisture content (%), green strength(g/),mould hardness, sand practical size(AFS).The Taguchi approach is used to capture the effect of signal to noise ratio of the experiments based on the orthogonal array used to find the optimum condition. The outcome of this paper leads to select suitable process parameters in casting industry to produce defect free castings. The improvement expected in reduction of casting defects is 20-30%.

2.4 Software applications

2.4.1 ProCAST Software

ProCAST is a leading finite element solution for casting process simulation. It can be used for direct chill casting; high pressure and low pressure die casting, investment and shell casting, sand casting, and lost foam casting. ProCAST is powerful tool to industry for new casting process development, process optimization, and problems solving and die designing.

It can predict temperature, liquid metal fluid flow, solidification and re-melting, heat transfer, distortion, cracking, shrinkage and porosity [31].

2.4.2 Minitab software

Minitab is a statistical analysis software package designed for carrying out statistical, numerical, and graphical activities. Minitab offers several graphical tools to explore and detect quality problems and improve process and hence it is an interactive program (i.e., supply Minitab with input data, or tell it where the input data is, and then Minitab responds instantaneously to any commands with that data) [32].

2.4.3 Analysis of Variance (ANOVA)

ANOVA is one of the most common statistical techniques for determining the percentage contribution of each input parameter on the results of experiments. Formally, ANOVA helps in testing the significance of all input factors and their interactions through comparing the mean square against the estimation of experimental errors at specific confidence levels. The main reason of using ANOVA in this analysis is to measure the significance of each process parameters on casting defects [33].

2.5 Summary of the literature

This section provides an introduction to sand casting process. First the steps of sand casting process were addressed. Then, considerations required for casting process design were stated. Next, casting quality and some common defects were discussed. After this, research works employed Taguchi’s methods of quality engineering were discussed in detail. Finally software’s like Minitab, ProCast and ANOVA application were discussed. Thus, what understood from the literature is how the Taguchi’s methods of quality engineering are a powerful tool in improving quality of products of manufacturing industries. The other understanding from the literature is that the basic roles of product/process design become true through a powerful application of Taguchi’s method of design of experiment. Casting simulation software were also discussed in this section, the casting simulation programs have different approaches in calculating and predicting the outcome of a casting. Therefore, Taguchi’s method and computer assisted casting simulation technique is a powerful tool that every manufacturing industry is better to utilize so that it helps them in producing quality products using product/process design strategies discussed above.

2.6 Literature Gap

Several attempts have been made by the researchers around the world to use the Taquchi methodology for process parameter optimization. But the researchers don’t addressed sand casting parameter optimization of the grey cast iron mill roller product. In this research work Taguchi method of Design of Experiments and computer assisted casting simulation techniques were combined to analyze sand cast mill roller defects. This study was also to predict the causes of the defects in the mill roller and the gating elements which account in the mill roller casting process. Therefore, clay and GFN of molding sand, design of gating system, and the optimal values of the parameters were determined.

CHAPTER THREE

3. MATERIALS AND METHODS

For successful completion of this research, numerical experiments were done, typical materials were selected, proposed methods were performed, appropriate tools and equipment's were used and relative sampling methods were chosen.

3.1 Product Selection for the study

Cast iron material was selected for mill roller component casting which has a low tensile strength, high compressive strength, excellent vibration damping properties, low ductility, high thermal conductivity, excellent machinability, excellent, cast ability, excellent wear resistance, poor corrosion resistance and cheap. The standard material used for mill roller casting is FG 260 grey cast iron.

3.1.1 Chemical composition of FG 260

In ABMI foundry FG 260 grey cast iron was selected for test of chemical composition analysis of carbon, silicon, phosphorus, Sulphur and manganese. Sample of pour was taken and tested prior to pouring using mobile spectrometer machine and percentage composition of the elements which take part were displayed as shown in table 3.1 below.

Table 3.1 Chemical composition of FG 260

Element	Carbon	Silicon	Phosphorus	Sulphur	Manganese	Iron
%	3.5	2.37	0.2	0.07	0.8	93.06

The standard composition of the grey cast iron FG 260 was shown in table 3.1. Due to slow solidification rate of grey cast iron, the iron-carbon binary phase diagram was insufficient to predict the phases and microstructures that they form. Therefore, sheet metals (approximate), Ferro-silicon and Ferro-Carbon were added in order to increase the amount of under-cooling required for the formation of cementite and promote the formation of graphite during solidification of grey cast iron. The amounts (masses) of Ferro- silicon and Ferro-carbon added to the induction furnace.

3.1.2 Mechanical Properties of FG 260

Grey Cast iron, also known as flake graphite cast iron, is a type of type of cast iron in which most of the carbon is present as flake graphite corresponding to form I of IS 7754. The property of Grey Cast Iron depends on the distribution, size and amount of graphite flakes, and the matrix structure. These factors are in turn, influenced mainly by the manufacturing conditions, chemical composition, solidification time and rate of cooling in the mould. Grey cast iron exhibit low to moderate strength, low modulus of elasticity, low notch sensitivity, high thermal conductivity, moderate resistance of thermal stock, and outstanding castability [60].

Table 3.2 Mechanical properties of FG 260 [60]

S/N	Mechanical properties	Value	Unit
1	Tensile Strength	260	MPa
2	0.01 % Proof Stress	73	MPa
3	Heat transfer coefficient	1000	$w/m^2/k$
4	0.10 % Proof Stress	169	MPa
5	Total strain at failure	0.57	%
6	Elastic strain at failure	0.20	%
7	Total minus elastic strain at failure	0.37	%

3.2 Materials used

The materials used in the mill roller castings were grey cast iron with the balance of the other elements, the mold materials (new and reclaimed silica sand), parting sand, resin (binders), catalyst (chemical), zirconium, dolomite powder(facing sand),alcohol, metallic paint, de-slagging agent, pure aluminum and asbestos were used.

Table 3.3 Materials used in the mill roller casting process

S/N	Types of materials	Specific name	Quantity	Unit
1	Cast iron	Grey cast iron	9520	Kg
2	Foundry sand	Mixed sand	16184	Kg
3	Parting sand	Parting sand	1455	g
4	Metal additives	Si, C,	480,120	kg
5	Sand binder	Resin	194.2	kg
6	Chemical(binder 2)	Catalyst	97.1	kg
7	Cavity paint	Iron cover	15	kg
8	Glue	Dolomite powder	5	kg
9	Pattern paint	Metallic paint	250	ml
10	Impurity removal	De-slagging agent	3	Kg
11	Cavity dryer	Alcohol	100	ml
12	Molten metal cover	Asbestos	150 × 150	cm
13	Furnace refractory	Neutral- Al_2O_3		

3.3 Research Methodology

To achieve the stated objectives, the following methodology was generally employed during the research process, Personal observation, Interview, discussion, collecting secondary data, Cause - effect diagram, Numerical experimentation, Modeling and Simulation technique.

First of all, the type of data's that was collected during the study in the selected company foundry was.

- The general background of the company foundry production system.
- Mill roller Product and process design parameters of the casting process of the foundry.
- Input variables to cast a mill roller.
- Quality characteristics of a mill roller being casted.
- Targeted quality parameters of a mill roller.

3.3.1 Data collection Methodology

Primary and secondary data were gathered using both quantitative and qualitative data collection methods. Different data collection methods were exploited to carry out this research thesis. These methods are:

1. Personal Observation

Besides of the survey questioners practical data has been gathered by the critical observation in the production areas of the factory foundry. Direct observation was carried out during molding, melting, casting (pouring) and composition inspection. During observation possible production parameters were tried to be identified. Un-deliberate changes in production variables by operators were also observed.

2. Interviews / Discussions

Interview or discussion has been conducted with selected body in the ABMI foundry. Individuals selected for interview/discussion were from the casting department managers, Casters, mold makers, pattern makers and quality control supervisor of the foundry. The interview/discussion was made on product/process development strategies that the company is using and other issues related with quality.

Here reported data was assessed and relevant information taken depending on the requirement. The Secondary data was collected from the reading different books, manuals, journals, web sites and visualization of shop of the company's foundry operational sections.

3.3.2 Cause-Effect Diagram

The parameters which are take account in the mill roller casting were Mould related parameters, Metal related parameters, Sand related parameters, Shake out related parameters, and Machine related parameters. The process parameters that affect the quality of mill roller during the production process were identified by using an Ishikawa diagram (cause and effect diagram). The Common uses of the Ishikawa diagram are product design and quality defect prevention, to identify potential factors causing an overall effect. Each cause or reason for imperfection was a source of variation and this diagram has been constructed as shown in figure 4.10. By using this diagram the various process parameters that affect the quality of the mill roller were identified.

3.3.3 Numerical experimentation

Design of experiments method such as Taguchi method can be efficiently applied for deciding the optimum settings of process parameters to have minimum rejection due to defects for a new casting as well as for analysis of defects in existing mill roller casting. Based on cause and effect diagram three process parameters namely moisture content, permeability and pouring temperature were selected to predict their effect on the filling of mold cavity as well as shape of mill roller castings (Table 4.7). For each process parameter three levels were selected which define the experimental region. The levels selected were based on the standards acceptable and foundry men experience in this organization for mill roller components castings. Three settings (levels) namely low-level, medium-level and high-level were chosen for each of the selected parameters. The number of experiments required for the three factors and three levels were determined using orthogonal array selector (Table 4.8). Effects of the selected parameters on the responses were determined using an orthogonal array, the signal-to-noise (S/N) ratio, and analysis of variance in Minitab 17.0 software.

The following steps of action (Methodology) were performed in determining sand casting process parameter optimization of mill roller using Taguchi method.

- Selection of any defect observed due to sand, mould and solidification during mill roller castings. Then target was Setted to achieve “lower casting defects” by adjusting the process parameters.
- Selection of the most significant parameters that influencing casting of mill roller defects by cause effect diagram.
- Selection of parameters and their levels. Experiments were performed as per DoE (Taguchi method) and data was collected.
- Analyze the data using statistical tools. Analyses of variance (ANOVA) were used to determine the statistical significance of the parameters. Means plots were plotted to determine the preferred levels of parameters considered for experimentation.

- Selection of the optimum levels of control parameters, perform confirmation experiments and implementation of the process action were performed.

3.3.4 Solid modeling of mill roller

Modeling was done with the help of solidwork (CAD) software and imported into FEM based software (proCAST) using geometry transformation. The materials selected for mill roller was grey cast iron and the dimension of mill roller was outer diameter 980 mm, inner diameter 500 mm and height 1840 mm respectively. Modeling consists of defining two parts one is sand mould and other is the castings with proportional dimensions. Elements which take account in the mill roller casting process are pattern, pouring cup, sprue and sprue base, ingate, riser and flasks were built using solidwork software. Then, all these elements were placed in with their respective positions and locations of the mold.

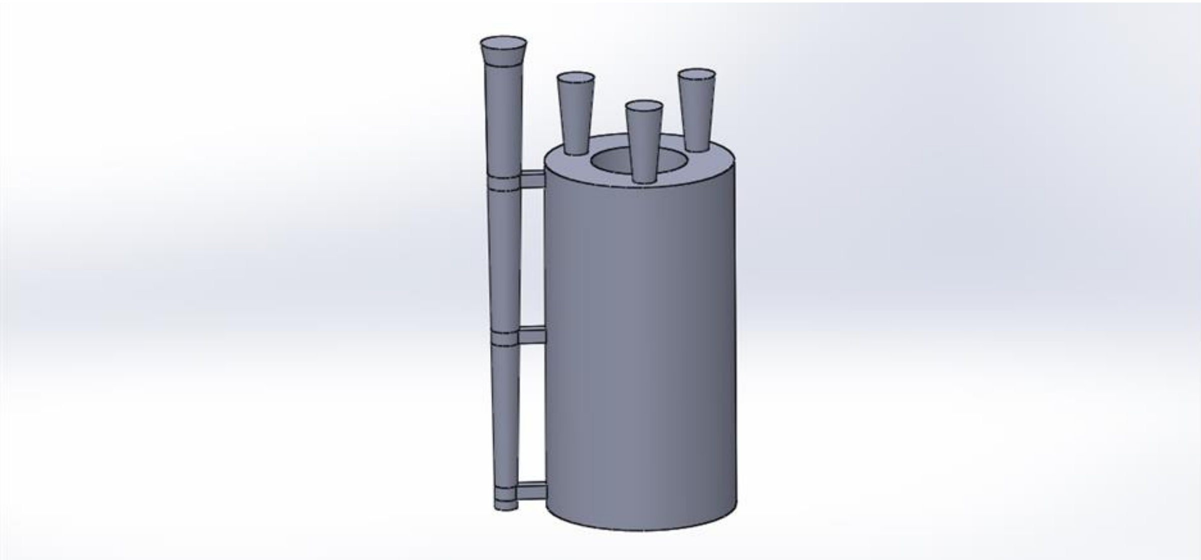

Figure 3.1 3D Geometry of mill roller with gating system

3.3.5 Casting Simulation

Simulation is the process of imitating a real phenomenon using a set of mathematical equations implemented in a computer program. The simulation programs are based on finite element analysis of 3D models of castings and involve sophisticated functions for user interface, computation and display. The casting model (with feeders and gates) has to be created using a solidwork software modeling system and imported into the simulation program (ProCAST software). In casting simulation the mold filling and solidification analysis were done by using an algorithm or program based on finite element method, to identify the defects and hence defects like shrinkage porosities, air entrapment, misrun etc. There are number of casting simulation software but the Simulation of the well-designed solidwork model mill roller casting process was carried out by using proCAST software. The

Prior to apply proCAST software for casting of mill roller is it can predict temperature, liquid metal fluid flow, solidification and re-melting, heat transfer, distortion, cracking, shrinkage and porosity. Generally the simulation software has three main parts: (1) Pre-processing (the program reads the CAD geometry and generates the mesh), (2) Main processing (adding of boundary conditions and material data, filling and temperature calculations) and (3) Post processing (presentation and evaluation).

Based on Finite Element technology, ProCAST provides a complete solution covering a wide range of simulation. The purpose of proCAST is to generate a finite element model, to setup the calculation, to run the analysis and, to interpret the results.

The following steps of action (procedures) were performed in casting process simulation of mill roller using ProCAST.

- 3D computer aided design of mill roller and all incorporating gating system using solidwork software.
- Save the CAD with IGES file format and import the CAD using geometry transformation tool to proCAST software.
- Mesh the mold and cast with surface mesh and volume mesh of 2D and 3D.
- Data input such as volume manager, interface HTC manager, process condition manager, and simulation parameters and start simulation by selecting ProCAST with number of solver is 4.
- Analyze the results with the view cast, such as temperature, solidification time, and fraction of solid and total shrinkage porosity.

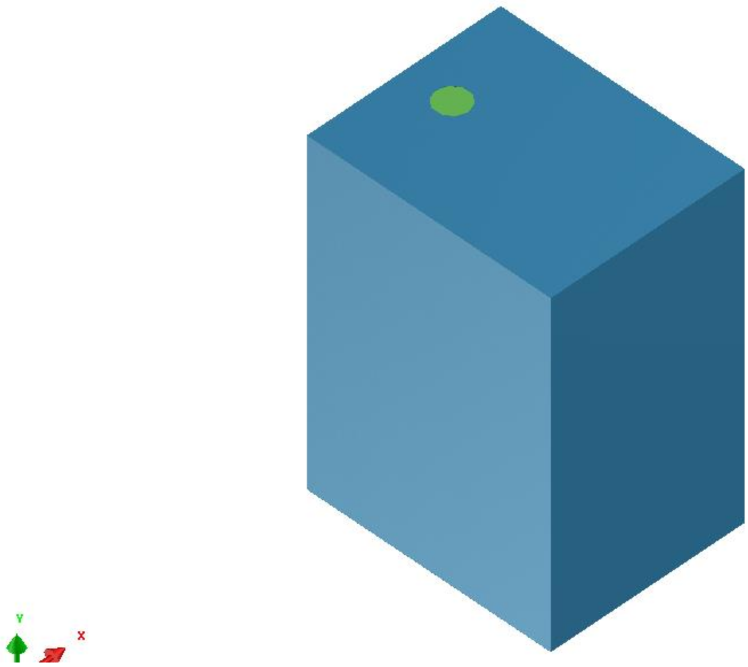

Figure 3.2 3D models of mill roller mold

3.4 Molding tools and equipment's used

Molding tools and equipment were used during the mill roller casting processes for the mold construction and completion of the mill roller casting processes are listed below in table as follows:

Table 3.4 Hand molding tools used in mill roller casting process at ABMI

S/N	Tool	Purpose
1	Steel stick	Remove impurities present on top of the molten metal by deslaging agent from the furnace and ladle
2	Center pin	Guide the flasks with each other and avoid mismatch
3	Venting and vent wires	Construct small holes on mold surfaces (flasks) in order to escape gas bubbles easily during solidification period.
4	Wood stick	For ramming the molding sand around the pattern within the flask and for maintain and finishing the gating systems
5	Gate knives	Cutting and finishing the unwanted parts of the mold
6	Meter	Measure dimensions of all parts which take part in the roller casting.
7	Screw	Assembled and disassembled the flasks
8	Mobile	Indicate room temperature of the foundry during mill roller casting

Table 3.5 Molding equipment used in mill roller casting process at ABMI

S/N	Equipment	Purpose
1	Flask	Prepared the mold used for molten metal receiving
2	Ladle	Holding the molten metal for pouring
3	Crane	Carrying the ladle from furnace to the mold
4	Mixer machine	Mix sand with resin and catalyst according to the provided ratio. It also used to inject molding sand to flask for ramming.
5	Sieve analyzer	Find the GFN of molding sand used in mill roller casting
6	Thermo couple	Find viewed the pouring and melting temperatures of the molten metal in the induction furnace.
7	Induction Furnace	Holding of 3500m^3 volume of liquid metal and used to charging the grey cast iron by electromagnetic induction principle
8	Manometer gauge	The gauge reading denotes the permeability number of the test specimen.

CHAPTER FOUR

4. DATA ANALYSIS AND CASE STUDY OF THE COMPANY

Akaki Basic Metals Industry is the major government owned model industry not only used for manufacturing metallic products but also used as a training and research center for all higher education engineering students and other researchers. The main concerns motivating the need for establishing this company was difficult to find spare parts for old machineries from former suppliers, very long delivery time that required gross orders and huge capital, need to place special orders due to difficulty to obtain regular spare parts, high foreign currency requirement to import the required spare parts [35].

Akaki Basic Metals Industry was established to make metal casting, forging, machining, heat treatment, automotive maintenance and quality control. It was intended to respond to the need of spare parts for textile, sugar, cement industries, other construction supplies, metal industries, transport sector and to some extent to agriculture, energy and mines sector. The company can cast up to 4,500 tons of metal in two shifts annually. The ferrous foundry can melt nodular iron, grey iron, low carbon and alloyed steels. The ferrous foundry section in ABMI is experiencing the general imperfections due to voids in most of its gray cast iron castings. The company uses grey cast iron for varieties of applications such as machine tool bodies, automotive cylinder blocks, heads, housings, fly-wheels, pipes and pipe fittings and agricultural implements. for a number of its customers that include all Sugar Factories, Muger Cement Enterprise, Hibret Machine Shop, Abijata Soda Enterprise, Gafat Armament, Ziquala Steel Mill etc. [35].

The study was focused on the grey cast iron castings of the foundry shop. In this section, the most critical sand casting process parameters of mill roller were analyzed which take into account the available data using the provided formulae and discussed as per the results found.

4.1 Data analysis of physical observation and interview

Data that were gathered with the help of above collection methods have been analyzed quantitatively and qualitatively. The data was analyzed using various tools available in Minitab software. These outputs have been presented with the supporting of tables, charts and graphical methods. The results from the data analysis have also been applied as an input to minimize the sand casting defect for ABMI foundry.

During mill roller casting it was physically observed that, sand casting of grey cast iron is affected by casting problems. Casting defects has been observed as the most representative quality characteristics in the mill roller sand casting process, as it is related to many internal defects sand sintering, solidification shrinkage cavity, porosity, surface roughness, misrun and slag.

An interview and discussion were carried out with the foundry experts like pattern sections, molding sections and melting sections to assess the critical casting process parameters of the mill roller and hence to gathered causes of the defects occurred. The data collected from interviews and discussion indicated that the variety of defects can be generated by equipment malfunction, process variation, some improper sand properties, improper gating system, labour problems and improper process operation in the mill roller castings.

Elements which take part in mill roller castings were determined to analyze casting defects developed during mill roller casting at Akaki Basic Metals Industry foundry and the study was focused only on grey cast iron mill roller casting.

4.2 Manufacturing of mill roller

Manufacturing of mill roller was done based on the design consideration of roller material and casting allowances. The design specifications of mill roller ordered by wonji sugar industries were given as net weight of 8106.1kilograms with the final dimensions of outer diameter Ø980 mm, inner diameter of Ø500 mm and 1840 mm height respectively. The 3D geometry of mill roller with the given specifications (initial) was built using solidwork software. The solidwork software by itself with the given dimension evaluate its net weight, its density, total volume and total surface area as 8568 kg, 7870.00 Kg/m^3, 1.03 m^3 and 1.03 m^2 using material mass properties tool of the solidwork software. The Geometry of the mill roller is shown in figure 4.1 and from this drawing pattern dimensions were prepared by taken some foundry allowances.

Figure 4.1 3D Geometry of the mill roller

4.2.1 Design specification of pattern

For manufacturing of mill roller a pattern was prepared in Akaki Basic Metal industry foundry by considering machining allowances, shrinkage allowances and draft angle.

Table 4.1 below discusses about the allowances given for the mill roller casting by the foundry pattern department. The shrinkage allowance given by the pattern section was enough for the grey cast iron castings due to slow solidification shrinkage behavior.

Table 4.1 Pattern allowances used in mill roller casting (taken from tabulated data sheet)

S/N	Parameter	Given	Unit	Remark
1	Machining allowance	5	mm	
2	Shrinkage allowance	1.3	%	
3	Draft angle	1	Degree	

A pattern made of wood was prepared in the pattern section with the final dimensions of the pattern diameter of Ø980 mm and 300 mm height respectively. For mould construction the pattern was used repeatedly 6 times. The 3D geometry of pattern with the given specifications (initial) was built using solidwork software. Hence, the net weight, total volume, surface area and density of the pattern used were evaluated as 32.99kg, 0.06m^3, 0.86m^2 and 560.00kg/m^3 respectively. The pattern size obtained from the solidwork software predicts about the overall size of the mill roller mold cavity filled by 9520Kg of molten metal. This is considered as the maximum weight of metal that filled in the mold cavity. The geometry of mill roller pattern is shown in figure 4.2

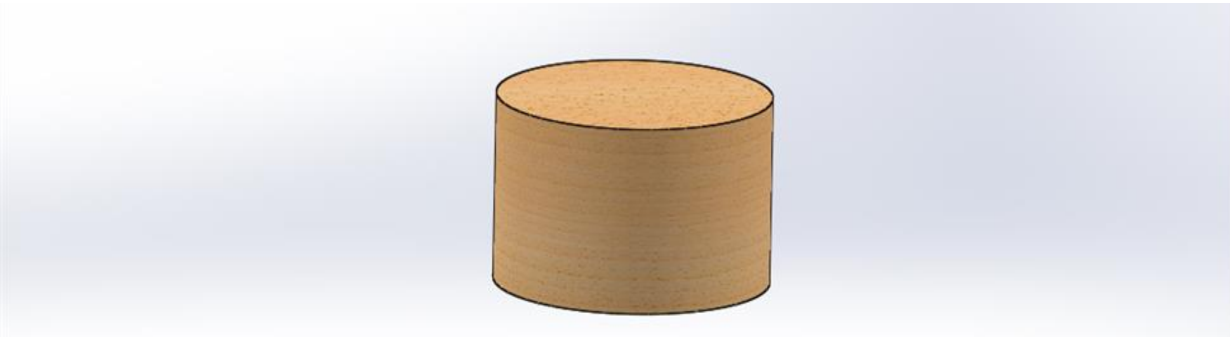

Figure 4.2 3D Geometry of the mill roller pattern

4.2.2 Flask selection

For casting of mill roller the gross weight of molten metal was poured in to the mold cavity, for this an appropriate flask was selected by considered the pattern dimensions, standard clearances between the cavity end and the flask inside walls. Since the gross weight of the casting is between 5000-10000 Kg, the minimum clearances was taken from Appendix A as

400 mm (a=b) in each side towards the mold height whereas 300 mm (c) is towards the width and 350 mm (d) along the length of the flask. Hence, the minimum required length of the flask for mold preparation was estimated as the sum of diameter of pattern, side clearances (along length), ingate length and riser diameter which was obtained as 1500mm. Similarly, the minimum required width was also determined as the sum of diameter of pattern, side clearances (toward width) and lengths of runner and sprue diameter which also obtained as 1500mm. Therefore, a flask near to these values was used with the dimensions given in Table 4.2 and Figure 4.3 (a) and (b) and the gating system elements were systematically constructed in the mold made on the inner surfaces of the flasks used.

Table 4.2 Overall dimensions of the flasks used in mill roller castings

S/N	Flask dimensions	Value	Unit	Remark
1	Length, L	1500	mm	
2	Height, H	321	mm	One flask
3	Width, W	1500	mm	
4	Thickness	10	mm	
5	Height of mold (metal)	300	mm	

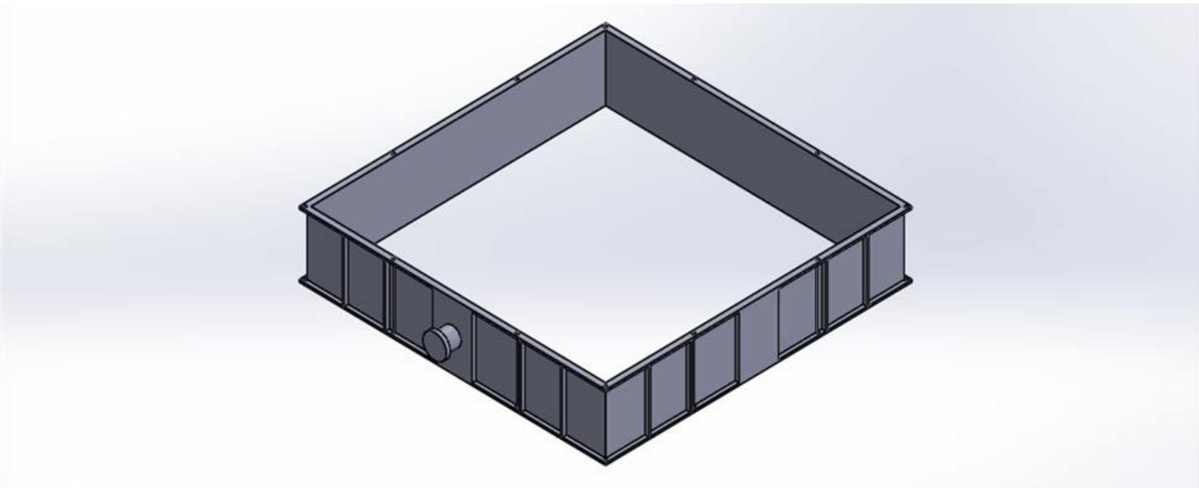

Figure 4.3 3D Geometry of the flask

4.2.3 Clay content analysis of mold sand

Clay in molding sand can be particles which fail to settle on a provided period when suspended in water. These particles are generally less than 20 microns in diameter. Thus, testing of clay content includes all very fine materials, fine silica and clay minerals [17, 35]. During mill roller casting process the clay content of the silica sand which used for mold making was determined for each sample taken experimentally.

The result of each sample test conducted was determined using equation (4.1) and given as percentage in table 4.3.

$$Clay\ content\ (\%) = \frac{W_{sb} - W_{sa}}{W_{sb}} \times 100 \quad \text{.........} \quad (4.1)$$

Where, W_{sb}-Weight of sand before washing, W_{sa}-Weight of sand after washing

The clay content percent for sample one was determined and found as follows

$$Clay\ content\ (\%) = \frac{100 - 93.15}{100} \times 100 = 6.85$$

Similarly for sample two, three, four and five found as 7.66, 5.27, 6.16 and 8.46 respectively.

Table 4.3 Clay content of the molding sand used

Sample	Weight before washed (g)	Weight after washed (g)	Clay content (%)
1	100	93.15	6.85
2	100	92.34	7.66
3	100	94.73	5.27
4	100	93.84	6.16
5	100	91.54	8.46

The clay content of the molding silica sand used in mill roller casting was determined as the average clay content result of the five samples taken given in table above. This was simply calculated from sum of all the clay content percentages divided by the number of samples and found as 6.88%. This is acceptable sand and its muddy effect was small.

4.2.4 GFN analysis of mold sand

The grain fineness number is a measure of average grain sizes derived by calculation from the result of sieve analysis. Molds made of very fine grained sands will be very packed and have little space between the sand grains that wouldn't allow entrapped air and gases to escape – leading to porosity defects. Those made of very coarse grained sands will be unnecessarily open to cause other casting defects. Therefore, the GFN values for molding sands shall remain within a certain range to obtain sound castings. For determination of GFN, percentage retained in each sieve is multified by its own multifing number (a constant for each sieve), and all the products are added. Grain fineness number of the molding sand is determined by taken a weighted sand sample using the following Equation (4.2) below [17].

$$GFN = \frac{sum\ of\ all\ the\ products}{sum\ of\ percentages\ collected\ in\ each\ sieve} = \frac{\sum M_i F_i}{\sum F_i} \quad \text{.........} \quad (4.2)$$

Where, M_i - multiplying factor (coefficient) for the ith sieve and F_i - amount of sand retained on ith sieve.

The grain fineness number of sand used in mill roller casting is given in table 4.4 below.

Table 4.4 GFN results of mixed sand used in mill roller casting

Sieve number	Gross weight (sieve +sand)	Sieve weight	Net. Wt of Sand	Percentage (%fi)	Coefficient No. (Mi)	Product (%fi x Mi)
11	425.16	425.12	0.04	0.04	5.5	0.22
10	402.74	402.38	0.36	0.36	7.5	2.7
9	364.68	364.13	0.55	0.55	10	5.5
8	374.98	373.28	1.7	1.7	20	34
7	353.15	341.32	11.84	11.84	30	355.6
6	344.52	317.08	27.44	27.44	40	1,097.6
5	341.14	321.75	19.39	19.39	50	969.5
4	329.68	309.30	20.38	20.38	70	1,426.6
3	309.18	306.95	2.23	2.23	100	223
2	303.26	302.43	0.83	0.83	140	116.2
1	307.60	307.09	0.51	0.51	200	102
Total			**85.27**			**4332.92**

The GFN of the mixed molding (silica) sand used in mill roller casting at the ABMI foundry was determined and found as 50.81. Based on this result, it was treated as very fine sand and therefore produced porosity on the mill roller casting due to the fact that the mold made from such type of sand could be compacted.

4.2.5 Determination of casting gross weight

The gross weight of casting can be defined as the weight of metal in mold cavity and weight of all gating system elements, i.e., net weight of the mill roller pattern casting plus the yielding material (excess weight of parts removed from casting by machining and grinding such as riser(s), riser base(s), sprue, sprue base, pouring cup and all ingates). For this work, the maximum casting yield of grey cast iron material was taken as 90% (Appendix E of Table E.1). So, casting gross weight was determined using Equation (4.3) as following [37].

$$Gross\ weight\ of\ casting\ = \frac{Net\ weight\ of\ mill\ roller\ casting}{maximum\ yield\ of\ grey\ cast\ iron\ casting} \cdots\cdots (4.3)$$

$$Wg\ = \frac{8568}{0.90}\ = 9520kg$$

This weight was considered as little good to get the desired mill roller weight of 8106.1 kg and also to fill the gating system cavities which take part in the casting process.

4.2.6 Refining and metal additives of grey cast iron

In ABMI foundry, Melting on grey solid metal used to be executed within establishment furnace yet degassing operation, elimination on oxygen gas beyond molten concerning grey cast metal used to be accomplished by adding clean aluminum according to molten within furnace then within after the preheated ladle earlier than poured done.

The pure aluminum added is believed in imitation of operate with the oxygen existing or shape CO bubbles and below outdoors beyond the melt. Hence, carbon execute remain decreased to the preferred extent after de-oxidation rendered (removal over the unsafe effect about high oxygen content material within the melt) durability.

4.2.7 Determination of pouring time

The pouring time to pour a molten metal of grey cast iron in to mold cavity to cast mill roller was determined and compared to the actual mold filling time which was taken during pouring. To determine this time of filling the fluidity factors of grey cast iron (k) and pouring temperature of grey cast iron was taken as 0.6079375 and 2372^{0}F. Therefore, this time of pouring for Gray cast iron mass greater than 450 kg was calculated using the empirical formula given in Equation (4.4) as,

$$\mathrm{t} = k(1.236 + \frac{T}{16.65})\sqrt[3]{w_g} \quad \cdots\cdots (4.4)$$

Where, k-fluidity factor of iron in inch, T- average section thickness in mm, Wg - mass of the casting in kg.

$$\mathrm{t} = 0.6079375(1.236 + \frac{240}{16.65})\sqrt[3]{9520} = 201.65s$$

This is the minimum time of pouring taken for the metal weight of 9520 Kg to completely fill the gating system and mold cavities.

4.2.8 Design of gating system

Gating System refers to all the sections through which the molten metal passes while entering into the mould cavity [31]. The gating systems which take part in mill roller casting were designed based on principles of pressurized type of gating in which reductions in cross-sectional areas of the passages to avoid backward pressure. Here most critical elements of gating system which take part in the process namely ingate, sprue, sprue base, pouring basin, riser and riser base were discussed in briefly in the following way.

A) Design of sprue

The passage which connects the pouring basin to the in-gate is called sprue. It is generally designed taper shaped in downward to avoid aspiration of air in sand casting because straight cylindrical shape creates a low pressure area around the metal of the sprue. It helps to feed molten metal without turbulence to the ingate which in turn reaches the mold cavity through gate. The sprue was designed based on the principle of law of continuity of mass “it states that the rate of flow of mass of the liquid is constant at any cross section" [38]. The actual diameter of the sprue at inlet cross section was taken as 10 cm; therefore the area of sprue is calculated from Equation (4.5).

$$\text{Area } = \frac{\pi * D^2}{4} \quad \cdots\cdots \quad (4.5)$$

$$\text{Area of sprue(at inlet)} = \frac{\pi * 10^2}{4} = 78.53\ cm^2$$

The diameter of the sprue up is equivalent to1.15 times the diameter of sprue at the outlet, hence from this relation it was determined that the diameter of sprue at the outlet were equal 8.7cm. Therefore the lower cross-sectional area of sprue (Area of sprue at exit) was determined similarly from the Equation (4.5).

$$\text{Area of sprue(at exit)} = \frac{\pi * 8.7^2}{4} = 59.45\ cm^2$$

The maximum height of a sprue was taken as equivalent to the height of mold in the mill roller casting as 1840mm and the actual sprue diameters which near to the designed values used were 100 mm as top diameter and exit diameter of 87mm with fillet radius 1mm, and height as 1840mm which is shown in figure 4.4 below. Therefore, the actual entrance and exit areas of sprue were calculated and found as 7853 mm^2 and 5945 mm^2 respectively.

Hence, the sprue has frustum like shape the volume of the metal in the sprue was calculated using frustum Equation (4.6)

$$\text{volume of sprue} = \frac{1}{12}\pi h\{D^2 + d^2 + Dd\} \quad \cdots\cdots \quad (4.6)$$

$$\text{volume of sprue} = \frac{1}{12} * \pi * 184.0\{10^2 + 8.7^2 + 10 * 8.7\} = 12654.1\ cm^3$$

$$V_{sprue} = 0.0126541 m^3$$

From the total volume of sprue the weight of the molten metal in the sprue was determined (density of the sprue material is 7870 kg/m^3) using the empirical formula (4.7)

$$Mass\ of\ material = \text{density of material} \times \text{volume of material} \quad \cdots\cdots \quad (4.7)$$

$$Mass\ of\ sprue = \ 99.59\ kg$$

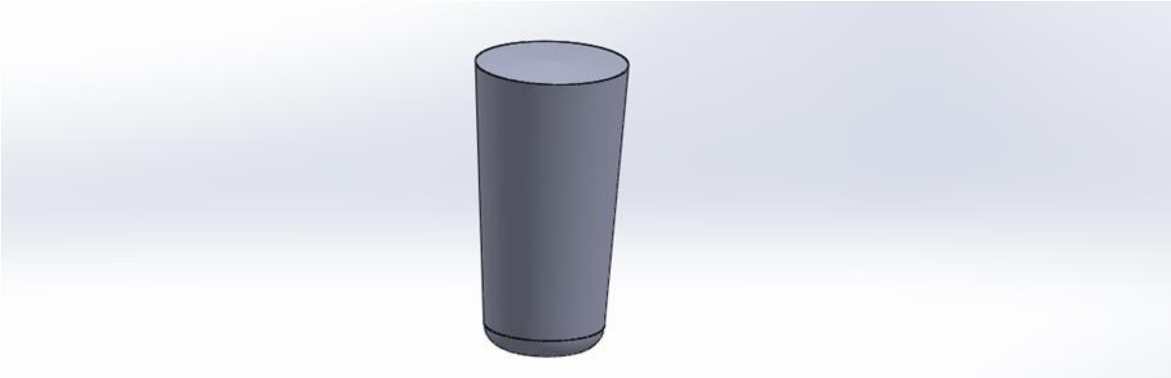

Figure 4.4 3D Geometry of the sprue

B) Design of Sprue base

Sprue base well is a reservoir for metal at the bottom of the sprue which reduces the mold erosion through reducing the momentum of flow metal. The pattern used in the mill roller casting of sprue base was grey cast iron pattern with dimension of 10cm top diameter, 7cm end diameter and 6cm height used for the construction of the sprue base cavity to received molten metal from the sprue exit to entrance ingate. The geometry of sprue base is given in figure 4.5. Hence, volume of the sprue base was determined similarly to Equation (4.6) using the following formula.

$$\text{volume of sprue base} = \frac{1}{12}\pi h\{D^2 + d^2 + Dd\} = 344.0\ cm^3$$

The weight of metal in the sprue base was determined similarly to the weight of sprue using Equation (4.7) and found as 2.71Kg.

This was comparatively good and hence produced pressure to the metal in the ingate. This amount of casting yield in the sprue base cavity was acceptable with respect to the given weight of mill roller casting.

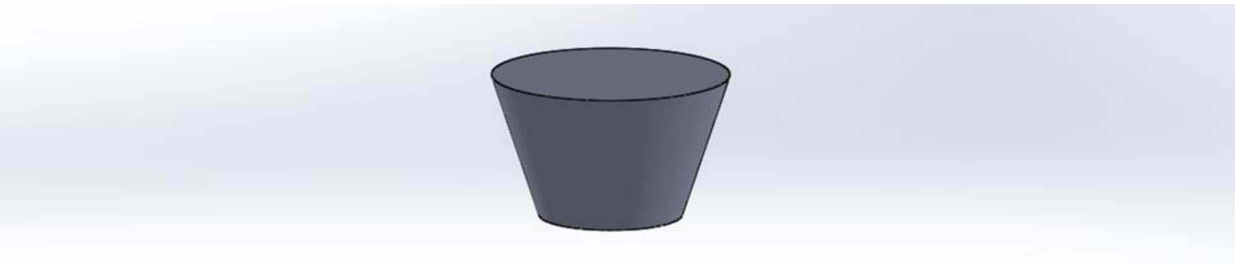

Figure 4.5 3D Geometry of the sprue base

C) Design of pouring basin

It is the conical hollow element or tapered hollow vertical portion of the gating system which helps to feed the molten metal initially through the path of gating system to mold cavity. A pouring cup with the dimensions of 10 cm entrance diameter, 8.7 cm exit diameter and 26 cm height respectively constructed on 720 mm × 570 mm × 380 mm cross section which was used for entrance molten metal into the cavity. The geometry of pouring basin is given in figure 4.6.

In Similarly way to the volume of sprue and sprue base the volume of molten metal and it weight in the pouring basin was determined using equation (4.6)

volume of pouring cup $= \frac{1}{12}\pi h\{D^2 + d^2 + Dd\}$ = 0.00178807 m^3

Hence, the total volume of the molten metal in the pouring cup was determined as 0.00178807 m^3 and the weight of the molten metal in the pouring cup was determined similarly equation (4.7) and found as 14.07 kg. This was also yield of the casting at the pouring cup of the gating system and it created pressure on the sprue cavity but lead to sand erosion because of its location. As a result, this made narrowed and even closed the sprue exit area and caused to metal solidification in the gating system and caused sand entered to mold cavity which is damage to cutter while machining.

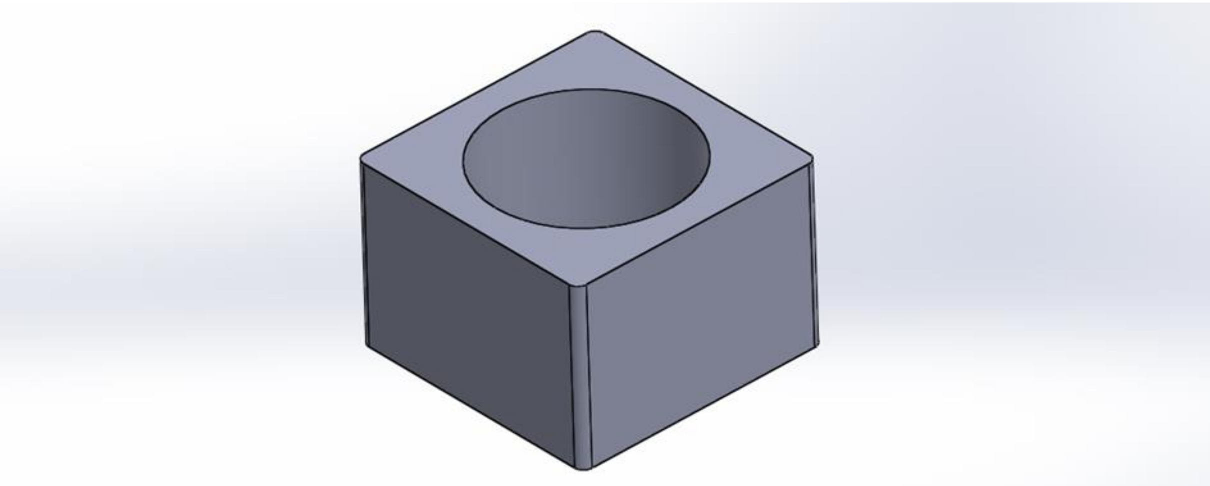

Figure 4.6 Geometry of pouring basin

D) Design of chock areas

It is the main control area which meters the metal flow into the mould cavity so that the mould is completely filed within the calculated pouring time. Therefore the chock area was determined from the following Equation (4.8).

$$A_C = \frac{W_g}{\rho m * t_p * \mu * \sqrt{2 * g * H}} \quad \text{......} \quad (4.8)$$

Where, A_C - chock area, W_g - casting mass in kg, ρm - density of liquid metal in kg/mm^3, t_p- pouring temperature in second, μ- efficiency factor which is taken as 0.8, H - sprue height in mm.

$$A_C = \frac{9520}{6.9 * 10^{-6} * 201.65 * 0.8 * \sqrt{2 * 9800 * 1840}} = 1424.17\ mm^2$$

The chock area of the gating system was determined as $1424.17\ mm^2$ hence; the diameter of chock value was determined and found to be 42.58 mm.

E) Design of total ingate areas

The flow rate of molten grey cast iron which entered to the mold cavity of the mill roller may be controlled by properly determined the number of ingates and designed their dimensions. The gating systems which take part in mill roller casting were designed based on principles of pressurized type of gating in which reductions in cross-sectional areas of the passages to avoid backward pressure. For pressurized gating system for grey cast iron the gating ratio was to be the following Equation (4.9) [31].

$A_C: A_R: A_G = 1: 1.3: 1.1$ ………………………………………………………………………… (4.9)

Where, A_C - chock area, A_R - area of runner but in mill roller casting runner is not used, A_G - total ingate area

$A_G = 1.1 * A_C$ ………………………………………………………………………………………… (4.10)

From Equation (4.10) formula total ingate area was determined and found as $AG = 1.1 * 1424.17 * 3 = 4699.76\ mm^2$ this area was the minimum area and treated as sum of all ingate areas constructed to the entrance of the mill roller mold cavity.

F) Number of ingates required

The number of ingates needed to fill a casting cavity in an acceptable time is determined by the size of the casting as well as the casting complexity [42]. The number of ingates required to feed molten metal to the roller cavity was determined based on casting geometry of the roller. Hence, the roller is very tall and hugs since three ingate was used for metal entrance to mold cavity, this total area of chock ($4699.76\ mm^2$) could be taken as the three ingate area. From this result, area of a single ingate was determined.

$$Ingate\ area, Ai = \frac{4699.76}{3} = 1566.59\ mm^2$$

The actual geometry of ingate used for mill roller casing was rectangular cross section with dimension of 15 cm × 7cm × 6.5 cm in construction of the ingate cavity as shown in figure 4.7 below. Therefore, ingate dimensions were obtained as 125.5 mm of width and 70mm of height (depth) using the width to depth relation of ingate sizes taken from Appendix B of Table B1.

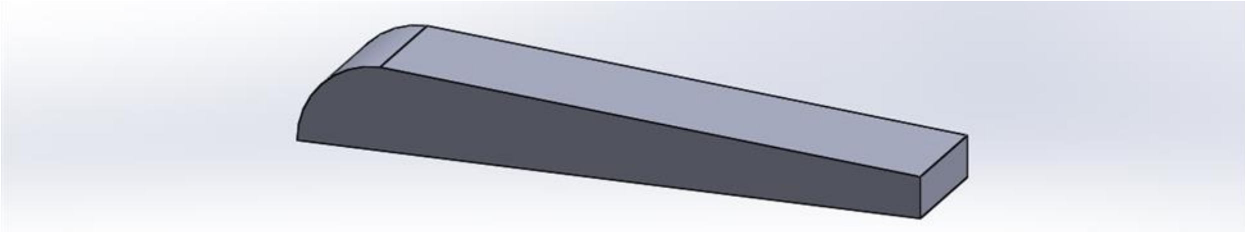

Figure 4.7 Geometry of the ingate

4.2.9 Design of riser

Feeders or risers are designed to compensate the shrinkage in the solidification of castings to eliminate porosities. A feeder or riser would act like a reservoir of liquid metal which would feed into an area of a casting which needs extra metal. Molten metal rises in it after filling the mould cavity completely. The molten metal in the riser compensates the shrinkage during solidification of the casting thus avoiding the shrinkage defect in the casting [12].

The designed riser of mill roller casting was considered to be large enough requirement so that it solidifies after the casting according to Chvorinov's rule and it must contain a sufficient volume of metal to supply the shrinkage contraction which occurs on cooling from the casting temperature to the completion of solidification. Solidification time of riser or casting which is related to properties of mold and metal which take part in the process determined using the formula of Equation (4.11).

$$Solidification\ time, t_r = C[\frac{volume\ of\ riser}{surface\ area\ of\ riser}]^2 \cdots\cdots (4.11)$$

Where, C is a constant that reflects mould material, metal properties like latent heat, and temperature. This condition of solidification in mill roller casting process was determined using the following formula of Equation (4.12) [12],

$$ts(riser > tS(casting) \cdots\cdots (4.12)$$

The section modulus of riser and the mill roller casting was determined by substituting the solidification time equation in to the above equation (4.8) and the relation was derived and found to the following formula Equation(4.13) [18],

$$CS(r) \left\{\frac{V}{A}\right\}^2 r > CS(c)\left\{\frac{V}{A}\right\}^2 c \cdots\cdots (4.13)$$

Where, CS(r) and CS(c) are the mold constants for the riser and casting respectively, and (V/A)r and (V/A)c are the volume to area ratios of the riser and casting respectively. Based on the literature review, constants CS(r) and CS(c) were considered as the same because of both the riser and mill roller were molded in the same material, i.e., silica sand. The section Modulus of riser (Mr) can be defined as the ratio of volume to area (V/A) r which was used as a critical parameter in riser design of sand casting process and also the section Modulus of casting (MC) can be defined as the ratio of volume to area (V/A)c. Thus the riser used in mill roller casting process was successfully designed by considered the CS(r) equal to the CS(c) using the following formula Equation(4.14),

$$(Mr)^2 > (Mc)^2 \quad \text{……} \quad (4.14)$$

Where, Mr > Mc - the criterion that must be met to insure that the riser solidified after the casting

Risers may be classified as top and side, hence their names, top risers are placed above a hot spot while side risers are placed at the side of the hot spot, usually at the parting line. In this study top riser was used for the mill roller casting process because top risers are more effective in the additional effect of gravity.

Sound casting produces when the solidification of the riser is taken as 1.5 times the solidification of the casting and also for top mounted riser solidification varies from 1 to 1.5 times diameter of the riser can take as satisfactory condition of feeding [41]. For larger castings, a cylindrical riser with spherical tops for a top riser was used. Based on this method diameter of riser was determined using the following Equation (4.15).

$$t_r = 1.5t_c \quad \text{……} \quad (4.15)$$

Therefore, by substituting solidification time equation (4.13) in to equation (4.15) for top mounted riser the top and exit diameters were determined as following Equation (4.16).

$$\{V/A\}^2\, r = 1.5\{V/A\}^2 C \quad \text{……} \quad (4.16)$$

$$(\frac{V}{A})r = 1.22(\frac{V}{A})c$$

During mill roller casting in ABMI foundry the shape of riser is cylindrical like frustum, hence the volume to surface area ratio was found using the following formula Equation (4.17) [36],

$$\frac{V}{A} = \frac{\pi hr}{12}(\frac{dt^2 + de^2 + dt * de}{Al + At + Ae}) \quad \text{……} \quad (4.17)$$

Where, A, AL, At and Ae- total surface area, latent area, top cross-sectional area and exit cross sectional area of the riser respectively also L-latent length of riser which was given in equation below. By substituting equation (4.17) into equation (4.16) the top diameter, exit diameter and height of the riser was determined. $L = \sqrt{\frac{(dt-de)+h^2}{4}} = 1.5120 \times dt$

In discussion, for top mounted riser the top diameter and the height of riser have the following relation in general dt = 1.15de and hr=1.5dt

$$V/A = 1.22(\frac{1.03\ m^3}{9.67\ m^2})c$$

dt = 0.260 m or 260 mm and possible maximum height of the riser, h= 1.5*d = 390 mm was found.

In order to avoid air aspiration that can be induced in the wall of the riser cavity during metal pouring the exit diameter of the riser was determined by considered the top riser diameter is equal to 1.15 times the exit diameter and determined as 226 mm. therefore, for mil roller casting the pattern near to the determined dimension (top diameter (dt), exit diameter (de) and height) was selected as 260 mm, 200 mm and 450 respectively and used in construction of mill roller cavity as shown in figure 4.8.

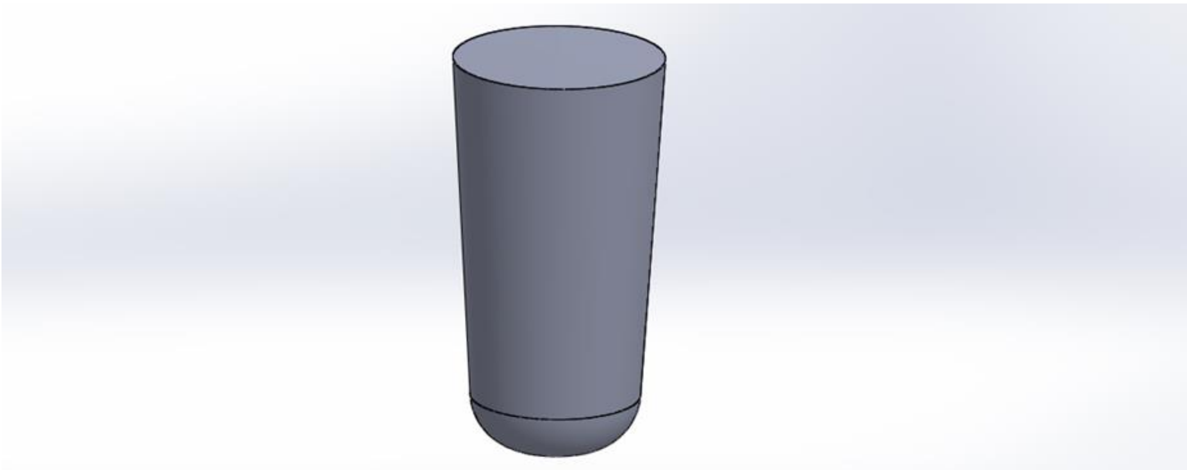

Figure 4.8 3D Geometry of the riser

This riser with the given sizes may be considered as good enough in metal compensation to the given mill roller cavity.

1) Riser volume

A feeder or riser would act like a reservoir of liquid metal which would feed into an area of a casting which needs extra metal. The volume of metal that reserved in the riser was determined on the basis of the actual dimensions using Equation (4.6) of the following formula [38],

$$volume\ of\ riser = \frac{1}{12}\pi h({d^2}_{top} + {d^2}_{exit} + d_{top} * d_{exit})$$

$$volume\ of\ riser = 0.0257m^3$$

The mass of molten metal in riser was determined from the total volume of riser and density of the riser material using the following Equation (4.7).

$$weight\ of\ the\ riser(w_{r)} = density\ of\ material * volume\ of\ material = 202.558\ kg$$

Based on this result the mass of molten metal that reserved in riser cavity was a little high because extra cavity was constructed in order to compensate the metal shrinkage but the casting yield was also high.

2) Riser neck

The connecting passage between the riser and casting, attached to it at the top face of the mill roller end. The neck facilitates easy to directed metal flow from riser to the riser base and then to the mold cavity of the mill roller. In addition, it also facilitates easy separation of the riser from the riser base. Hence, the neck was considered as an important part of the riser. Therefore, for top mounted riser, diameter of the riser neck was determined from top riser diameter and its neck height using the following Equation (4.18) [39],

$$dn = Ln + 0.2 * D \quad \cdots\cdots (4.18)$$

Where, dn – end riser neck diameter, Ln - riser neck distance from the casting, D - riser top diameter

For this design the actual top diameter of the riser pattern was considered and the neck distance from the casting was considered to be D/2 which was found to be is 130 mm.

Therefore,

$$dn = 130 + 0.2 * 130 = 182\ mm`$$

Hence, the actual riser neck which used in mill roller casting process was with a pattern dimension of 182 mm end diameter and 130 mm of height and attached with the riser.

3) Determination of number of riser

The number of risers required to feed molten metal of grey cast iron to the mill roller cavity was determined based on the casting geometry and feeding distance required. Using top riser formula for a riser with MR of 1.5d / 7, gives a cylindrical riser with diameter of 26cm and height of 50cm.The risers and each casting end can be effective on promoting a sound casting immediately adjacent to either the roller end or the riser. The sound distance from the riser along the roller is termed as Riser Effect (RE) and the sound distance from the end of the roller is also termed as end effect (EE) [40].

For cast iron casting the RE and EE were taken as 2T cm and 2.5Tcm respectively. The contribution to sound casting from each riser would then be the riser diameter plus 2RE (feeding in both directions). Then, the maximum distance fed for each riser was 2(RE) plus riser diameter. The number of risers required along the diameter of the mill roller allocated in circular pattern uniformly from the end of the roller was determined using the following formula (4.19) [41].

$$Number\ of\ risers = (2D - EE)/(2RE + d) \cdots\cdots (4.19)$$

Where, D-Diameter of the mill roller, EE- End Effect, RE-Riser effect

Number of risers = (520 - 2EE) / (2RE + 260) = 2.72 = 3 riser

Based on the size of the mill roller casting and riser location, three risers were needed and the design used to determine the number of risers was acceptable.

4) Determination of feeding distance

The feeding distance (FD) is the maximum distance over which a riser can supply feed metal such that the casting section remains relatively free of internal porosity. Hence, the number of risers required was determined by the feeding distance. According to this, effectiveness of the risers decreased when the feeding distance of a riser exceeds its limit and therefore shrinkage may be developed. The feeding distance of a hot riser for grey cast iron mill roller castings, used could be approximated on either side of the riser with a proper thermal gradient using the following formula (4.20) [12].

$$FD = 4.5T \cdots\cdots (4.20)$$

Where, FD - the feeding distance and T - the thickness of the section being fed.

$$FD = 4.5 * 48 = 216cm$$

Therefore, the minimum distance was determined as 216 cm. hence it predicts that the riser was effective in feeding metal towards the height of mill roller.

5) Design of Core

Core is considered as an individual unit sited in a mould to fabricate a corresponding cavity, undercut in the casting process. Cores are also used for producing complex features which cannot be produced otherwise, by using a pattern or mould individually. Cores are typically made of sand that is mixed with organic binders such as linseed oil or cereal. Organic binders are preferred over clay because they break down under the heat of the molten alloy, which makes them easy to remove during shakedown. The raw sand mixture is typically molded in a core box to form the core. After molding, the core is baked in an oven to give it the strength it needs to be handled during placement in the mold and to withstand the fluid flow and buoyancy forces that may develop during filling and solidification of the casting [40].

The core constructed for casting of mill roller was by having diameter of 500 mm and height of 1840 mm. this core should have enough strength to maintain integrity throughout the casting process and also collapse and revert to sand after solidification so that it is easy to remove. Cores are made by ramming or blowing the raw sand mixture into a core box. Metal rods are sometimes used to strengthen the core.

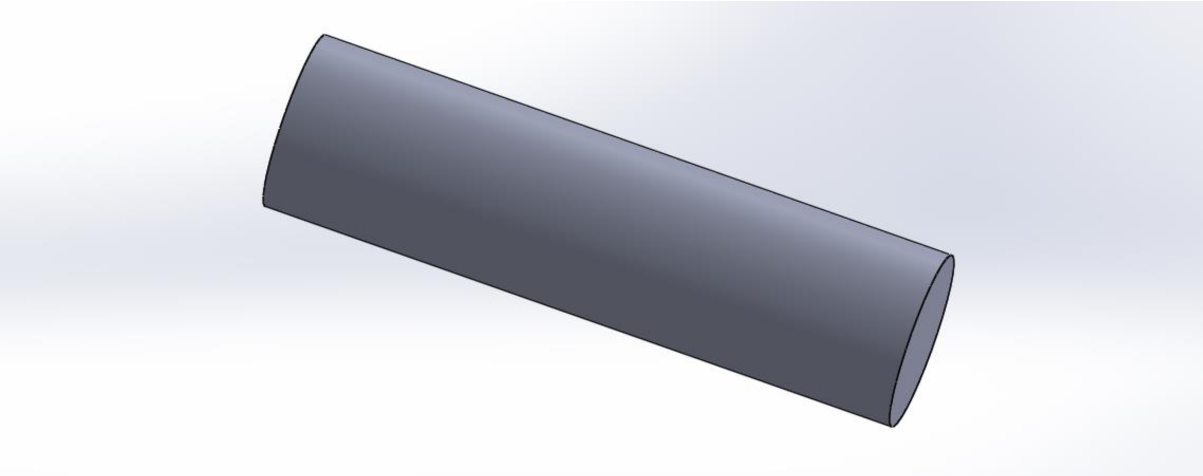

Figure 4.9 3D Geometry of the core

4.2.10 Determination of casting to riser freezing ratio

To ensure the solidification shrinkage or macro porosity in the mill roller to be avoided solidification time of the riser to solidification time of mill roller casting was compared in terms of relative freezing time or freezing ratio of casting to riser. Therefore, relative freezing time or freezing ratio (RF) of riser to casting was determined using Equation (4.21) based on modulus method as following [37],

$$R_F = \frac{(\frac{volume}{surface\ area})riser}{(\frac{volume}{surface\ area})casting} \quad \cdots\cdots (4.21)$$

$$R_F = 0.4469$$

According to this method the volume to area (V/A) ratio of the riser is 0.0476, as compared to the casting V/A ratio of 0.1065 (i.e., V/A of riser is 0.4469 times V/A of casting longer).

According to this result the riser freezing period predicted that much larger than the casting freezing period and the riser was solidified after the casting and should feed properly hence produced sound mill roller castings.

4.2.11 Determination of pouring speed

The gap between the ladle lip and the pouring cup (entrance of the sprue) was measured and found as head variation from 80cm (when the molten started to leave the ladle tip i.e., fall freely from a starting velocity of zero) to 55cm (at the optimum ladle level).

The maximum velocity of the molten metal at the pouring cup base was determined after falling a distance of 80cm and 55cm plus the height of pouring cup respectively using Equation (4..22) by ignored the coefficient of friction (free stream) as following,

$$v_p = \sqrt{2gh_p} \quad \cdots\cdots (4.22)$$

Where, v_p- pouring speed in m/se at a particular distance, g - acceleration due to gravity i.e., 9.81 m/sec^2 (assumed constant) and h_p- pouring head in meter.

Therefore, velocity of the metal at the pouring cup bottom and or sprue entrance from the two heads respectively,

$$v_{0.80} = \sqrt{2 * 9.81 * (0.80 + 0.26)} \text{ = 4.56 m/sec}$$

And

$$v_{0.55} = \sqrt{2 * 9.81 * (0.55 + 0.26)} \text{ = 3.99 m/sec}$$

From the velocity results, the first velocity was believed to occur for short duration whereas the second velocity was performed up to pouring completion. The first velocity may be created erosion of sprue lip. Thus, for this work the velocity of 3.99 m/sec was taken for other analysis of metal flows in the channel used in mill roller casting.

The maximum critical velocity of the metal arrived at sprue bottom or exit was determined by considered the surface friction coefficient (μ) of the sprue-wall using Equation (4.23) of the following formula,

$$v_{max} = \mu\sqrt{2 * g * h_s} \quad \text{(4.23)}$$

Where, v_{max} - pouring speed in m/se and h_s - sprue height in meter which is 1840mm.

Therefore,

$$v_{p,exit} = 0.2 * \sqrt{2 * 9.81 * 2.1} \text{ = 1.28 m/sec}$$

This is considered as the critical velocity of metal in the sprue exit which was influenced the metal speed in the critical gating systems channels and treated as moderate speed for grey cast iron casting flow on the sprue base.

The dimensionless Reynold's number (Re) was also determined using Equation (4.24) to determine the fluid flow condition at the sprue entrance and exit sections [40].

$$Re = \frac{\rho VL}{\mu} = \frac{VL}{v} \quad \text{(4.24)}$$

Where ρ - the fluid density which is taken from Appendix E of Table E.2, V - the velocity of the fluid at the sprue entrance and exit(determined), L - important length dimension for the flow (for pipe flow, L is taken as the pipe diameter D_H (hydraulic diameter) which is sprue diameter). μ - the dynamic viscosity taken from Appendix E of Table E.2, and υ - the kinematic viscosity where υ =μ/ρ.

Therefore,

Re=43,292 and 59,539.76 (in sprue entrance and exit respectively)

Also the Reynolds number in the ingate (circular sections of the gating system) was calculated using Equation (4.25).

$$R_e = \frac{\rho V D_H}{\mu} = \frac{\rho V}{\mu}\frac{4A}{P} \quad (4.25)$$

Where, D_H - equivalent hydraulic diameter ($D_H = \frac{4A}{P}$), A – cross-sectional area and P - wetted perimeter (total perimeter of all channel walls that are in contact with the flow of each ingate element, i.e., Perimeters of ingate are 44cm). The equivalent hydraulic diameters of the ingate are 9.55 cm. Therefore, Reynold's numbers (Re) in the ingate were obtained as 43,954.47.

4.2.12 Determination of riser solidification time

The total time required to freeze a riser for the grey cast iron mill roller casting was determined using the following Equation (2.26) the materials considered both in riser and casting was the same.

$$t_r = [\frac{\pi}{4}\left(\frac{\rho_{c\Delta H_f}}{T_m - T_o}\right)^2 \left(\frac{1}{k_m \rho_m c_m}\right)] \left[\frac{(V)}{(A)}\right]^2 \quad (4.26)$$

Where, t_r - solidification time of riser, ρ_m, c_m and k_m- are density, specific heat and thermal conductivity of the mould material respectively (Appendix E of Table E.3), and H_f - latent heat of solidification, ρ_c - density of liquid metal casting (Appendix E of Table E.2), V - volume of riser solidified, A - interface area of the riser, T_m - melting point temperature (℃) and T_o– initial temperature of mold wall (℃). In this, the properties are assumed to be constant all over the casting process. Therefore, Total solidification time (TST), t_r = 48.095 = 2 day. According to this result, the riser solidified after casting solidification completed and predicted that the design carried out was acceptable in produced sound mill roller casting.

4.2.13 Determination of average flow rate of mold cavity filling

The average flow rate the molten metal of the mill roller was determined simply dividing the gross weight of casting divided by the actual time of filling, using Equation (4.27) of the provided formula[40],

$$Q_{ave} = \frac{W_g}{t} \quad (4.27)$$

Where, Q_{ave} - average flow rate of casting in kg/sec, W_a- the actual weight of elements which take part in mill roller casting in kg and weight of the mill roller in the mold cavity and t - actual filling time in seconds.

$$Q_{ave} = \frac{9520\ kg}{800.55\ sec} = 11.89\ kg/sec$$

This is the average of metal weight flow to the mold channel cavities and predicted that 11.08Kg per every second may be feed in the cavities of the gating system.

The mold filling time of the mill roller mold cavity was also determined using Equation (4.28) of the following formula [36],

$$MFT = \frac{Mold\ cavity\ volume}{volumetric\ flow\ rate} = \frac{V}{Q} \quad \cdots\cdots (4.29)$$

Where, V - volume of the mold cavity of the mill roller which is $0.103m^3$ and Q - volumetric flow rate of metal along the mold channels which determined from the velocity and sprue bottom cross-sectional area ($0.00076096m^3/sec$)

$$MFT = \frac{1.03m^3}{0.0076096\, m^3/sec} = 135.35\ sec$$

This is the minimum time required to filling the mill roller mold cavity only (by ignored the gating system elements' cavity).

4.2.14 Determination of flow rate and metal flow along mold channels

The flow rate of molten metal along the mold channels or the volumetric flow rate of metal in the passages which take part in mill roller casting, the initial velocity of metal at the ladle tip was assumed as zero. Velocity of metal at the entrance of sprue was determined after falling down through the heights and found as 4.56 m/sec and 3.99 m/sec. respectively. But the metal can be entered with a velocity of less than the determined one due to the fact that the difference of the pouring cup bottom and sprue entrance dimensions (sprue top diameter is less). By assumed the volumetric flow rate of metal remain constant and then metal velocity at top of sprue was estimated by applying the continuity law of Equation (4.30) as following [36],

$$Q = A_1V_1 = A_2V_2 \quad \cdots\cdots (4.30)$$

For the mold channels the volume flow rate and linear velocity flow was determined from Equation (4.30) above as follows,

$$Q_1 = A_1V_1 = A_2V_2$$

Where, Q_1 = Volume flow rate at the sprue inlet cross-section, A_1= entrance sprue cross-sectional area, and V_1= linear velocity of flow at sprue entrance

Hence,

$$Q_1 = 0.0076096\, m^3/sec \quad and \quad V_1 = 0.97\, m/sec$$

Similarly, Volume flow rate at the sprue exit cross-section and velocity at sprue exit cross section was determined using the following Equation (4.30),

$$Q_2 = A_1V_1 = A_2V_2$$

Where, Q_2 = Volume flow rate at the sprue exit cross-section, A_2= exit sprue cross-sectional area, and V_2= linear velocity of flow at sprue exit,

$$Q_2 = 0.076174\, m^3/sec\ and\ \ V_2 = 1.28\, m/sec$$

This is the maximum flow rate result (Q_1) of molten metal flow through the entrance of the sprue without considered the surface tension. Thus, actual flow rate can be believed lower than from what is estimated above.

Similarly, Volume flow rate at the ingate inlet and outlet cross-section and velocity of the metal at ingate inlet and outlet was determined using the following equation (4.30),

$$Q_3 = A_2V_2 = A_3V_3$$

$$Q_3 = 0.0076096\, m^3/sec\ \ and\ \ V_3 = 1.77\, m/sec$$

Where, Q_3 = Volume flow rate at the ingate inlet and out let cross-section, A_3 = actual ingate inlet and exit areas and V_3 = velocity of metal at ingate inlet and outlet section.

4.2.15 Determination of temperature loss to the gating system

Grey cast iron material was melted and poured at optimum meting and pouring temperature to ensure no misrun and penetration defect occur. At the furnace the pouring temperature was taken as 1300 ℃ (during pouring from ladle to sprue entrance of the mold), due to heat losses in the gating system the molten metal does not enter in to the mould cavity at the pouring temperature. Therefore, there was temperature drop during liquid metal pouring time at the gating system. Hence less fluidity caused misrun defect or penetration defect on the casting product. Therefore, the amount of temperature of the molten grey cast iron loss in the gating system was determine using Equation (4.31) as following [43],

$$\Delta T = \frac{Asc(T_p - T_{mi})(\sqrt{t_p}\ )}{W_tC_i}\sqrt{K_m\rho_m C_m} \quad \text{………………………………………………} \quad (4.31)$$

Where, Asc - surface area of the mold channel used (sum of the surface channels of all ingate system (cm^2), T_p - pouring temperature (°C), T_{mi} - initial temperature of the mold(°C), t_p- pouring time(in sec), W_t - weight of the casting and the gating system(kg), C_i - specific heat of liquid metal (taken from Appendix E of Table E.2), J/Kg× °C, K_m - thermal conductivity of the mould material , J/se/m×°C, ρ_m, - density of the mould material, Kg/cm^3, C_m - specific heat of the mould material, J/Kg×°C which given by $\sqrt{K_m\rho_m C_m}$ - Heat diffusivity (J/m$^{2\times}$K×s$^{1/2}$) (taken from Appendix E of Table E.4).

Table 4.5 given below discusses about the critical casting process parameters taken through direct observations during metal melting, pouring, filling and part removal activities.

Table 4.5 Data related to melting and casting of grey cast iron used

S/N	Parameter	Experimental	Unit
1	Pouring temperature	1250, 1270, 1300	℃
2	Melting temperature	1127, 1130, 1204	℃
3	Room temperature	25	℃
4	Pouring head used	80,55	cm
5	Mold filling time	135.35	sec
6	Part take off time	58	Hrs.

In this case, the total surface area of the mold channel, that made in contact with fluid, was determined believed that more heat may be loss within the channel surfaces and found as 4403.28 cm2 or 0.0.44032797 m2 (sum of all surfaces in contact with fluid).

Table 4.6 Surface area of mold channels in the contract with fluid

S/N	Chanel	Total surface area	Area in contact	Unit
1	Sprue	$A_L + A_t + A_e = 6914.70$	$A_L = 6778.72$	cm^2
2	Sprue base	$A_L + A_t + A_e = 277.24$	$A_L + A_e = 198.7$	cm^2
3	Ingate	$2A_c + A_L = 141.82$	$A_L = 136.22$	cm^2
Total			4403.28	cm^2

The results given in Table 4.6 discuss about the total surface area of the mold channels which take part in mill roller casting and areas of these channels that only made contact with fluid flow during mold cavity filling from sprue entrance to ingate section.

Where, A_L- lateral area, A_t - top area, A_e - exit area and A_c - cross sectional area of the passages (mold channels) used in the mill roller casting. Therefore, the los is determined as

$$\Delta T = \frac{0.0.44032797\ m^2 (1300℃ - 25℃)(\sqrt{201.65\ sec}\ )}{9520\ kg * 554\ J/kg℃} * 3.21 * 10^3\ J/m^2 * K * s^{1/2}$$

$$\Delta T = 0.485℃$$

The loss of temperature in the gating system channels was found to be 0.485℃ and hence hot metal was arrived to ingate outlet cavity with a temperature of approximately 1299.5℃.

4.2.16 Solidification process of mill roller casting

The process of solidification, the change of liquid to solid metal after pouring into the mold, is the defining event in the life cycle of a casting. The times involved in this activity may be as short as seconds or as long as hours depending upon the casting process and the size of the casting. The chemical composition of the metal being cast, the manner in which solidification occurs, and the subsequent solid state treatment determines the ultimate microstructure and therefore properties (mechanical and physical) of the casting [42]. The system turned into first of all designed primarily based on directional solidification principle which sweeps metal from the extremity of the mould cavity towards the riser. Vent holes have been constructed on mold to let loose the fuel bubbles which are crucial reasons to porosity formation in the mill roller. Then, the molds made was stand in 90o from horizontal stage and metal changed into poured through the designed gating device and consequently cavities had been filled. Solidification of the metallic becomes finished via natural modes of heat transfer (conduction and convection). The next region of the melt may be act as riser and compensated metal to the first extraction area made via the riser.

4.3 Selection of process parameters

The control factors have significant effect on the percentage rejection of mill roller component. The parameters were setted and maintained based on the discussion with foundry managers, casters, mould makers and pattern makers but cannot be directly changed the customer. Noise factors include variation in environmental operating conditions. According the literature, the study conducted in the casting industry shows, 70% of the rejection are due to moulding sand related parameters, 20% of the problems are due to pouring metal related parameters and remaining 10% of defects are due to melting, pattern shop and core related parameters [44]. Due to this phenomenon, the sand and pouring metal related parameters was only selected for this work. If the parameters were not properly selected, casting defects such as sand drops, sand crush, mould breaking, loose ramming, shift, swell, cold shut, blow hole, shrinks and hot tears may be caused.

The factors that were to be considered must also affect the rate of solidification directly or indirectly as it also determines the formation of grey cast iron. The most significant and measurable parameters were identified by the means of Ishikawa diagram (cause effect diagram).

4.3.1 Cause and effect diagram

Cause and effect diagram is a tool for identifying the root causes of quality problems [45]. The process parameters that affect the quality of mill roller during the production process were identified using an Ishikawa diagram (cause and effect diagram). This diagram has been constructed as shown below in figure 4.9. By using this diagram the various process parameters that affect the quality of the mill roller were identified. The identified process parameters were Mould related parameters, Metal related parameters, Sand related parameters, Shake out related parameters, and Machine related parameters. The process parameters can be listed in five categories as follows:

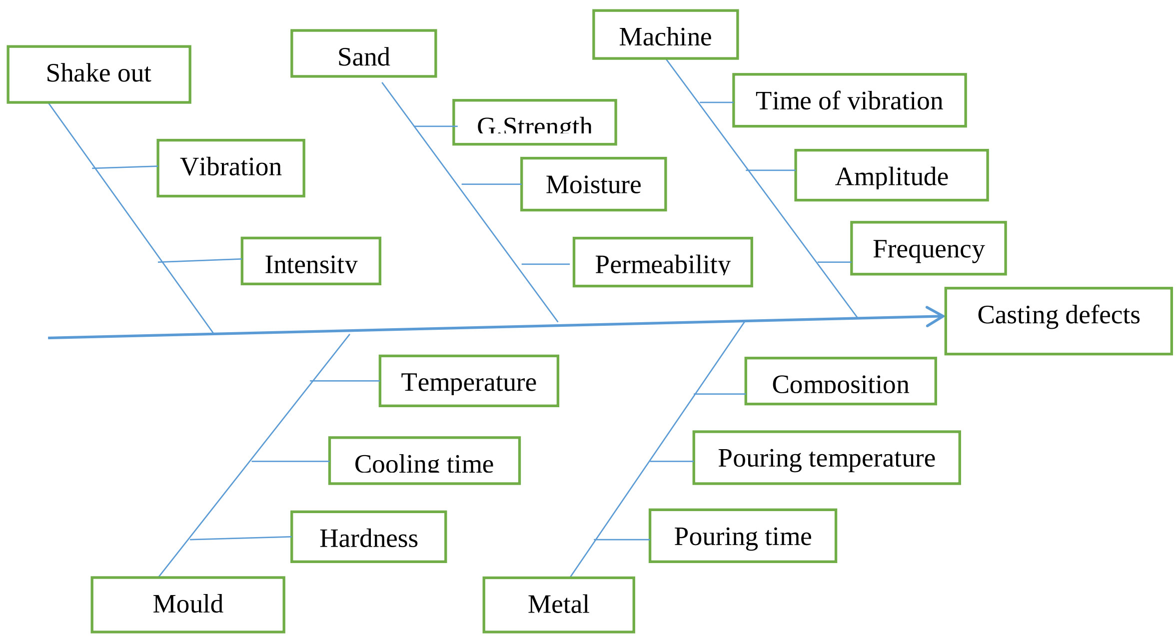

Figure 4.10 Cause and effect diagram

In order to visualize the effect of parameters on the mill roller sand casting defects the following parameters were selected. The parameters are permeability (115 - 145), pouring temperature (1250°C – 1300°C) and moisture content (2%– 3%).

4.4 Designing an experiment

When designing an experiment, the factors, relevant interactions, and the factor levels need to be determined. In the Taguchi method, two to five levels are usually recommended. While using the Taguchi method, the experiment is designed by following the column assignments specified by an orthogonal array (OA). The orthogonal design employed is based on the number of factors, their levels and the number of selected interactions. In this research work three level orthogonal arrays were used. The most common orthogonal array for three level factors used are L9 (3^3) and L27 (3^7) etc. Therefore L9 was found to be most appropriate to study 3 factors at three levels. Here data were collected for mill roller component of a company foundry production system, and Minitab 17 software was used to analyze the data so that it helps to conclude which process factors mostly affect the output response factors of the products.

Minitab offers four types of designed experiments: factorial, response surface, mixture, and Taguchi (robust). Among these types of designed experiments Taguchi method (orthogonal arrays) was selected. To apply the Taguchi's method of design of experiment the process input parameters in table 4.7 was used.

4.4.1 Experimental variable and level selection

The process variables considered in this study were moisture content, permeability and pouring temperature. These process parameters (control factors) can affect the quality of mill roller products. Three levels were selected for each control factor. The specific factor levels were selected based on discussions with the production personnel of the company and most repeatedly occurring settings in the company foundry production process of mill roller.

Table 4.7 Variables and settings selected for experimentation

S/N	Name of variable	Factor letter	Low - level (1)	Medium - level (2)	High – level (3)
1	Permeability (No)	A	115	135	145
2	Pouring temp. (°C)	B	1250	1270	1300
3	Moisture content (%)	C	2%	2.5%	3%

4.4.2 Selection of an orthogonal array

The non-linear behavior among the parameters of sand casting process can only be determined if more than two levels of parameters was used [26]. The number of levels for each control parameter defines the experimental region. For each control factor, three levels were selected. The levels should be chosen sufficiently for apart to cover a wide experimental region because the sensitivity to noise factors does not usually change with small changes in control factor settings. Also, by choosing a wide experimental region, that can be identified good regions, as well as bad regions, for control factors. Therefore, each parameter was analyzed at different levels based on the behavior of process parameters.

The selection of OA depends on the following:

1. The number of factors and interactions of interest
2. The number of levels for each factor of interest

These two items determine the total degrees of freedom required for the entire experiment. The degrees of freedom for each factor are the number of levels minus one. The degrees of freedom for the factors under investigation, DOF, assuming no interactions is given as;

$$DOF = 1 + (\#\ of\ Factors) * (\#\ of Levels - 1) \cdots\cdots (4.32)$$

Where, DOF - is total degree of freedom.

Therefore,

$$DOF = 1 + (3) * (3 - 1) = 7$$

The system degree of freedom (Do) available in an OA is equal to the number of trials minus one i.e.

$$D_o = N - 1 \cdots\cdots (4.33)$$

$$D_o = 9 - 1 = 8$$

In order to select the particular orthogonal array for an experiment the following inequality must be satisfied.

$$DOF \leq D_O$$

As it can be seen that for the product total degree of freedom *DOF* is less than or equal to the system degree of freedom D_O selected for the product. Therefore, the selection of orthogonal arrays (OA) is feasible.

The standard Taguchi's orthogonal arrays selected were shown in the table of appendix D.

4.4.3 Conducting an experiment

To conduct experimental investigation (depending on the recorded data) for mill roller products Minitab 17 statistical software was used. L9 (3^3) orthogonal arrays were used for mill roller production depending on their number of factors affecting the quality of product. From the recorded data of the foundry found that different response values were registered for the each factor settings of process parameters, in which case it was filled in the column of response place (example, trial 1 and trial 2). The detailed experiment and list of the results was shown below.

4.5 Experimental analysis and Results

The following analyses were performed here: the mean response analysis and the S/N response analysis. The mean response analysis shows the factors that have the greatest impact on the mean of the response distribution and the S/N analysis show the factors that have the greatest impact on the variance and mean of the response distribution. In the Taguchi method, the signal to noise ratio (S/N) is used as the data transformation method that consolidates the data for each control array row over the various noise levels into one value which computes both the mean and the variation present in the data.

The equations for calculating the signals to noise ratios are based on the characteristics of the response variables being evaluated; nominal the best, smaller the better and larger the better. The smaller the better number of casting defect implies better process performance.

Table 4.8 Field in Orthogonal array of three variables and three states

Trial No.	Permeability (%)	Pouring Temp. (℃)	Moisture content (%)
1	115	1250	2%
2	115	1270	2.5%
3	115	1300	3%
4	135	1250	2.5%
5	135	1270	3%
6	135	1300	2%

7	145	1250	3%
8	145	1270	2%
9	145	1300	2.5%

Numerical experiments were conducted twice for the same set of parameters by using single repetition randomization technique. Subsequently the percentage of defect for each repetition and for each trial condition was taken from data sheet of the company. The percentage of defects for each repetition was calculated by using Equation (4.34),

$$\% \, of \, defects = \frac{No. of \, defects \, occurring \, due \, to \, moulding \, process}{Total \, no. of \, defects \, occurring \, in \, the \, process} \quad \cdots\cdots\cdots\cdots \quad (4.34)$$

Table 4.9 below discuses about the Trials conducted in nine experiments with twice replicate of each factor levels.

Table 4.9 Trials conducted in nine experiments with two replicate

Trial No.	**A**	**B**	**C**	**Trial 1**	**Trial 2**
1	115	1250	2%	6	5.3
2	115	1270	2.5%	4.7	4.5
3	115	1300	3%	5.6	5.3
4	135	1250	2.5%	5.7	7.2
5	135	1270	3%	5.4	5.3
6	135	1300	2%	4.7	4.1
7	145	1250	3%	3.6	4.6
8	145	1270	2%	3.2	4.8
9	145	1300	2.5%	2.8	3.4

The selected input factors of casting process have an effect on the quality of miller was predicted experimentally and the results has been shown in table 4.10. The casting defects are the "smaller the better" type of quality characteristics. Signal to noise ratio and the mean of the casting defects were determined for each trial condition.

The performance characteristic factors of the process namely, the mean and signal to noise ratio of each experiment were determined to predict the effects from the replicate results using the following equations respectively [34, 35],

$$Mean = \frac{sum \, of \, individual \, trials \, of \, each \, experiments}{n} \quad \cdots\cdots\cdots\cdots \quad (4.35)$$

$$S/N \, ratio = -10 \log(\left(\frac{1}{n}\right) \sum_{i=1}^{n} y^2 ij \quad \cdots\cdots\cdots\cdots \quad (4.36)$$

Where, S/N ratio - is used for measuring sensitivity to noise factors, n - is number of experiments in orthogonal array and Y^2_{ij} – is the i^{th} values measured. Table 4.10 below discuses about the mean and signal to noise ratio of each experiment calculated using Equations of (4.35) and (4.36) respectively.

Table 4.10 Mean and Signal to Noise ratio of the experimental trials

Trial No	A	B	C	Trial 1	Trial 2	Mean	S/N ratio
1	115	1250	2%	6	5.3	5.65	-15.0576
2	115	1270	2.5%	4.7	4.5	4.60	-13.2572
3	115	1300	3%	5.6	5.3	5.45	-14.7312
4	135	1250	2.5%	5.7	7.2	6.45	-16.2495
5	135	1270	3%	5.4	5.3	5.35	-14.5675
6	135	1300	2%	4.7	4.1	4.40	-12.8892
7	145	1250	3%	3.6	4.6	4.10	-12.3198
8	145	1270	2%	3.2	4.8	4.00	-12.2115
9	145	1300	2.5%	2.8	3.4	3.10	-9.8677

4.5.1 Analysis of Signal –to- Noise ratio (S/N)

As an evaluation tool for determining the robustness of the design, 'signal-to-noise' ratio (S/N) is the most important component of the factor design. In the Taguchi method, the term 'signal' represents the desirable target (higher percentage of approved castings) and 'noise' represents the undesirable value [29].

After the responses collected, Signal-to-Noise (S/N) ratios was determined for all the responses. Since the objective of this work is minimization of casting defects that were observed during mill roller casting. The smaller-the-better type category was considered for the analysis. The S/N ratio for each factor level was calculated using Equation (4.36).

Table 4.11 S/N ratio results of each experiment conducted

Trial No.	A	B	C	Trial 1	Trial 2	S/Ni
1	1	1	1	6	5.3	-15.0576
2	1	2	2	4.7	4.5	-13.2572
3	1	3	3	5.6	5.3	-14.7312
4	2	1	2	5.7	7.2	-16.2495
5	2	2	3	5.4	5.3	-14.5675
6	2	3	1	4.7	4.1	-12.8892
7	3	1	3	3.6	4.6	-12.3198
8	3	2	1	3.2	4.8	-12.2115
9	3	3	2	2.8	3.4	-9.8677

In Table 4.11 observed that the SN ratio values of distribution in each experiment were conducted and varied from minimum of -16.2495 (4^{th} row) to maximum of -9.8677 (9^{th} row). The average SN value of each factor and level was calculated from the SN ratio of each experiment using the following Equation formula [33],

$$SN_{A1} = \frac{(S_{N1} + S_{N2} + S_{N3})}{3} \quad (4.37)$$

After average S/N ratio values of each factor and level was calculated the range (Δ) of each factor was determined by substracting the larger value from the least small value with in a factor, then based on the range of each factor the rank was given table 4.12 below

Table 4.12 Effect of each factor on response variable

Level	**A** (Permeability, No)	**B** (Pouring Temp, °C)	**C** (Moisture content, %)
1	-14.35	-14.54	-13.39
2	-14.57	-13.35	-13.12
3	-11.47	-12.50	-13.87
Δ=(max-min)	3.10	2.05	0.75
Rank	**1**	**2**	**3**

From the S/N response table 4.12 permeability and pouring temperature have the greatest effect moisture content have the least effect on the output response of the product mill roller.

4.5.2 Main effect plot for SN ratios

Numerical experimentation predicted the effect of each selected factor using Minitab software from the overall mean line of signal to noise ratio.

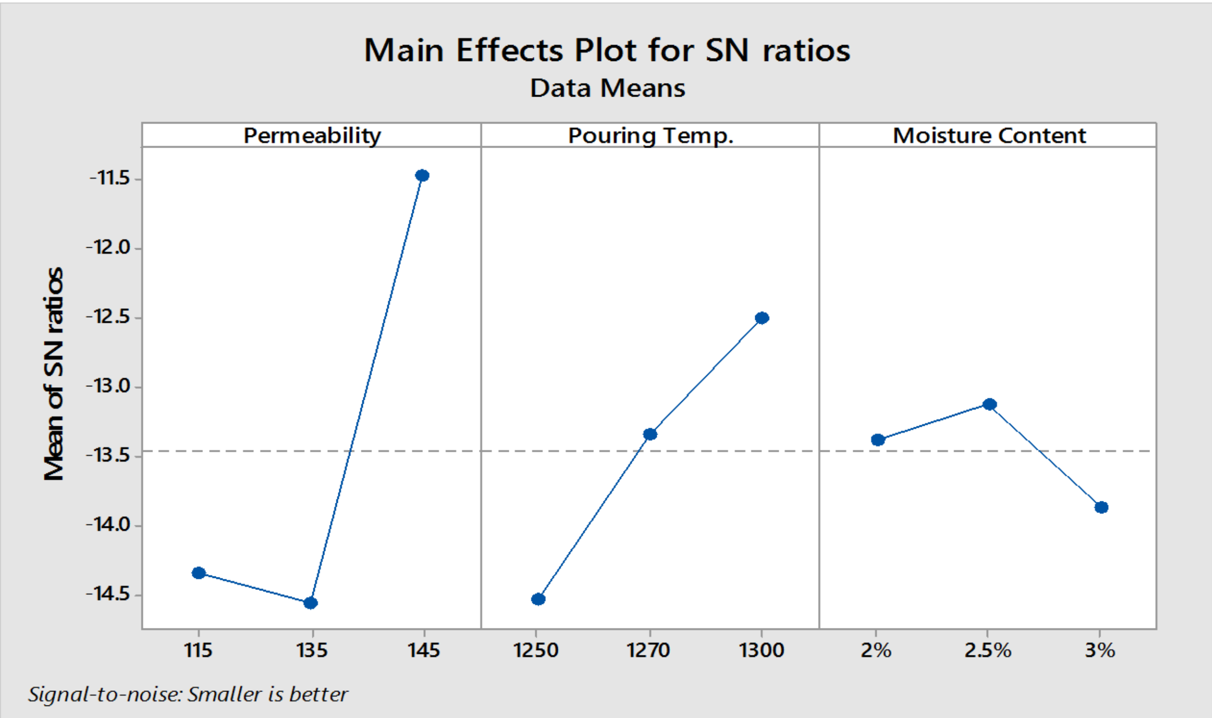

Figure 4.11 Main effects plot for S/N ratio values

From figure 4.11, it can be observed that Permeability of sand mold and pouring temperature is the most influential factor for changing the percentage of casting defects and moisture Content has less effect.

4.5.3 Analysis of Variance (ANOVA)

The analysis of variance is to determine the control factor that significantly affects the quality characteristics. ANOVA establishes the relative significance of factors in terms of their percentage contribution to the response which take part in mill roller casting process.

After the experiments were conducted, the ANOVA is used to analyze the results of the experiments. The significant factors and/or their interactions were identified, for various trial conditions and the parameters which significantly influence the casting defects.

Table 4.13 Analysis of Variance for S/N ratios

Source	DOF	SS	MS	F-ratio	P- value	Percentage Cont. (%)
A	2	17.9810	8.9905	4.36	0.186	61.35
B	2	6.3412	3.1706	1.54	0.394	21.64
C	2	0.8647	0.4323	0.21	0.827	2.95
Error	2	4.1196	**2.0598**	*	*	
Total	8	29.3064	14.6532	*	*	100

From the selected factors permeability contribution was larger and has the larger ability to influence signal- to-noise ratio (S/N) according to the experimental method used.

4.5.4 Pooling of Error

The combining of column effects to get better estimate error variance is referred to as pooling. The pooling up strategy entails F-test the smallest column effect against the next larger one to see if significance exists. If no significant F-ratio exists, then these two effects are pooled together to test the next larger column effect until some significant F ratio exists. Pooling-up will tend to maximize the number of columns judged to be significant, and it will be used by us to lead us to the verification experiment.

The percent contribution and F-ratio of moisture content were insignificant and hence they were pooled with the error estimates along with the degrees of freedom, sums of squares, variance to regenerate the table as result of pooling up strategy employed.

These factors are pooled to obtain new, S_e and f_e

Sum of squares of error:

$$S_e = S_T - (S_A + S_B) \quad \cdots\cdots 4.38$$

$$S_e = 29.3064 - (17.9810 + 6.3412) = 4.9842$$

Degree of freedom of error term:

$$f_e = f_T - (f_A + f_B) \quad \cdots\cdots 4.39$$

$$f_e = 8 - (2 + 2) = 4$$

Variances of error calculate as:

$$V_e = \frac{S_e}{f_e} \quad \text{4.40}$$

$$V_e = \frac{4.9842}{4} = 1.24605$$

Table 4.14 Results of analysis of variance after pooled error.

Source	DOF	SS	MS	F-ratio	P- value	Percentage Cont.
A	2	17.9810	8.9905	4.36	0.186	61.35%
B	2	6.3412	3.1706	1.54	0.394	21.64%
Pooled						
Error	4	4.1196	**1.24605**	*	*	17.01%
Total	8	4.9842	*	*	*	100%

4.6 Raw data analysis of experimental results

The mean response refers to the average value of the performance characteristics for each parameter at different levels. The average values of the response at each parameter level was obtained by adding the results of all trails conditions at the level considered, and then dividing by the number of data points added.

The average percentage of casting defect and S/N ratio for each parameter at different levels were given table 4.15. Hence, the results in Table 4.15 indicated that the percentage of defects was minimum and maximum S/N ratios at third level of permeability (A_3), third level of pouring temperature (B_3) and 2nd level of moisture content (C_2).

Table 4.15 Average values of casting defects and S/N ratios

Factors	Level 1		Level 2		Level 3	
	Casting defects	S/N ratio	Casting defects	S/N ratio	Casting defects	S/N ratio
A	5.233	-14.35	5.400	-14.57	3.733	-11.47
B	5.400	-14.54	4.650	-13.35	4.317	-12.50
C	4.683	-13.39	4.717	-13.12	4.967	-13.87

4.7 Interpretation of experimental result

Numerical Experiments was conducted using Minitab 17 software and ANOVA was carried out using the result obtained from the experiments. The significant factors and their interactions were identified, graphs were plotted for various trials conditions and the parameters which significantly influenced the mean and variation in the percentage rejection was carefully determined. The interpretation method is as follows [46]:

- Estimation of mean
- Percent contribution
- Confident interval

4.7.1 Estimation of Mean

A numerical experiment was done and an optimum treatment condition within the numerical experiment was determined. The response graph clearly shows that the optimum sand cast mill roller parameters was obtained at lower percentage defect and maximum S/N ratios. The most direct way to estimate the mean for that treatment condition was to average all the results for the trials which were set at those particular levels. The determination of mean for casting defects of mill roller was calculated by using Equation (4.38),

$$\mu = T + (A3 - T) + (B3 - T) + (C2 - T) \quad \cdots\cdots (4.41)$$

$$\mu = A3 + B3 + C2 - 2T \quad \cdots\cdots (4.42)$$

$$\mu = 3.733 \ + 4.317 + 4.717 - 2 \times 4.788$$

$$\mu = 3.19$$

Where, μ = mean percentage defect at the optimal sand casting mill roller parameters, T = total average defect of all control factors (T = 6.389), A3 = average casting defect when factor A is at level 3, B3= average casting defect when factor B is at level 3 and C2= average casting defect when factor C is at level 2.

4.7.2 Percent contribution

The percent contribution is the portion of the total variation observed in an experiment attributed to each significant factor and or interaction which is reflected thereof. The percent contribution is a function of the sums of squares for each significant item. It indicates the relative power of a factor and interactions to reduce the variations [46]. Table 4.13 shows Analysis of Variance for casting defect including percent contribution at 95% confident level.

4.7.3 Confidence interval

The mean (μ) is the only point estimated based on the average of the results obtained from the numerical experiment. Statistically this provides a 50% chance of the true average being greater than μ and a 50% chance of the true average being less than μ. The confidence level is between the maximum and minimum value, which the true average should fail at some stated percentage of confidence [46]. In this research work, confidence interval (CI_3) around the estimated mean of a treatment condition used in a confirmation experiment to verify predictions and calculated using Equation (4.40),

$$CI_{CE} = \sqrt{F_\alpha(1,f_e)V_e\left[\frac{1}{n_{eff}}+\frac{1}{R}\right]} \quad \text{(4.43)}$$

$n_{eff} = \frac{18}{1+[8]} = 2,\ f_e = 2\ V_e = 2.0598$ α = 1- confidence limits (95%) = 0.05 $F_{0.05}(1,2) =$ 18.51(tabulated).

$$CI_{CE} = \sqrt{18.51 \times 2.0598 \times \left[\frac{1}{2}+\frac{1}{2}\right]} = 6.17$$

Where, α = level of risk, $F_\alpha(1,f_e)$ = the F- ratio at the confidence level of (1-α) against DOF 1 and degree of freedom, f_e= error DOF, $n_{eff} = the\ effective\ number\ of\ replications,$ $n_{eff} = \frac{N}{1+[DOF\ associated\ in\ the\ estimate\ of\ mean\ response]}$ N = total number of observation = 18 R = number of test trials = 2, and V_e = error in mean square. DOF associated in the estimate of mean response = 8.

Predicted optimal range (for a confirmation runs of two experiments) at 95% confidence interval is:

$$Mean(\mu) - CI_{CE} < \mu < Mean(\mu) + CI_{CE} \quad \text{(4.44)}$$

$$\mu - CI_{CE} < \mu < \mu + CI_{CE}$$

$$-2.98 < 3.19 < 9.36$$

4.8 Confirmation of experiment

The confirmation run was used to determine that the selected control parameter values will produce better results than those produced in the first part of the experiment. The confirmation experiments were used to verify that the factors and levels chosen from an experiment cause a product or process to behave in a certain fashion. If the average of the results of the confirmation is within the range of the confidence limits, then the significant factors as well as the appropriate levels for obtaining the desired results are properly chosen. If the average of the results of the confirmation experiment is outside the range of the CI, the parameters selected and/or levels to control the results for a desired value are incorrect or have excessive measurements, necessitating further experimentation [15].

Three confirmation experiments were conducted at the optimum settings of the process as shown in Table 4.16. The average of the respondents casting defects in each experiment was found to be 8.6%, which was within the CI of the projected value of the casting defects. The confirmation experiments results gave 8.6<9.36% (maximum of CI). Therefore, the selected parameters as well as their appropriate levels were significant enough to obtain the desired result.

Table 4.16 Mill roller sand casting result of confirmation experiment

Experiment	Percent of casting defect		Average percent of casting defect
	Trial 1	Trial 2	
1	7.8	8.6	8.2
2	8.6	9.4	9
Total average			**8.6**

4.8.1 Confirmation of Results

In this research study, the Taguchi optimization method was applied to find the optimal parametric combination which minimizes sand cast mill roller defects. Table 4.17 shows percent contribution and optimum parameters under economic considerations. Among the three parameters, the hierarchy of process variables affecting the casting defects was experimentally determined. The optimal percentage of defect in mill roller casting process was determined with a minimal number of experimental runs.

Table 4.17: Percent contribution and optimum parameters under economic consideration

Parameter	Parameter	Mean of casting defects	S/N ratio of casting defects	Optimum level	Optimum value
A	Permeability (No)	60.26%	61.35%	3	145
B	Pouring Temp (℃)	22.01%	21.6%	3	1300
C	Moisture cont. (%)	1.71%	2.95%	2	2.5

Figure 4.12 Cast product of mill roller

4.9 Casting process simulation

ProCAST is powerful tool to industry for new casting process development, process optimization, and problems solving and die designing. It can predict temperature, liquid metal fluid flow, solidification and re-melting, heat transfer, distortion, cracking, shrinkage and porosity [31].

Generally the simulation software have three main parts namely Pre-processing (the program reads the CAD geometry and generates the mesh), Main processing (adding of boundary conditions and material data, filling and temperature calculations) and Post processing (presentation, evaluation). The following steps of casting process simulation were carried out using proCAST software. The input for the proCAST was geometric model created in solidwork software which is given in figure 3.1; this 3D modeled geometry was saved in IGES format and imported in to the proCAST software. Then in visual mesh first of all the 3D model was repaired and assembled, if problems is identified CAD design may be changed. Then 2D surface mesh was created by defining edge group element size and checked for surface mesh was ok and also 3-D volume mesh was created. For volume manager silica sand and grey cast iron was selected as molding material and alloy element with 25 ℃ and 1300 ℃ as initial working temperature. For interface manager, coincident was selected with the interface condition of h= 1000 $W/m^2/k$. For process condition manager, thermal and fluid flow was applied with heat air cooling boundary condition and with inlet 11.87 kg/s mass flow rate as the boundary condition. For simulation process parameter, gravity casting was applied and thermal model activation; porosity model activation and TH-Module are on. Finally simulation started by selecting numbers of cores 4. Casting simulation program provides output files in the form of graphical images and video files which are analyzed to predict defects after the successful execution. The mesh geometry of mill roller incorporating with all the gating system is given below in figure 4.13.

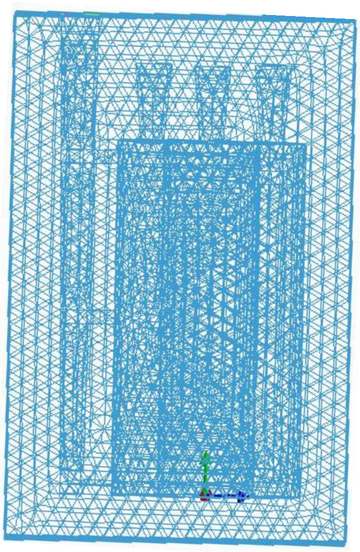

Figure 4.13 3D Geometry of meshed mill roller

Table 4.17 Input material properties and conditions

Input parameters	**Specific name**	**Description**
Alloy element	Grey cast iron	EN-GJL-300
Mold material	Silica sand	
Initial temperature of alloy element	1300℃	
Initial temperature of mold	25℃	
Heat transfer coefficient b/n alloy element and mold	1000 $w/m^2/k$	
Pouring temperature of alloy element	1300℃	
Boundary condition of mold	Air cooling	
Boundary condition of alloy element	11.87kg/s	Mass flow rate

4.10 Casting simulation Analysis

Casting simulations results fail in three major aspects of a complete metal casting process namely filling, solidification, and stress analysis. ProCAST was used to simulate fluid flow and solidification of sand casting of mill roller. Casting simulation and result analysis was done to predict the molten metal solidification behavior inside the mold. It requires solid models of product and tooling (parting, cores, mould layout, feeders, feed aids and gates), temperature dependent properties of part and mould materials, and process parameters (pouring temperature, rate, etc.) The simulation results can be interpreted to predict casting defects such as shrinkage porosity, hard spots, blowholes, cold shuts, cracks and distortion [46].

The output criteria which can be displayed in ProCAST is filling time, solidification time, critical fraction solid time, temperature gradient, cooling rate and shrinkage porosity. Each of these simulation results reveal sources and causes of casting defects that can be occur in roller and these provide an opportunity to rectify any errors prior to a physical casting process in ABMI foundry.

4.10.1 Filling process analysis

Fill time represent time taken on which the particular part of the component is filled by the liquid metal. The flow of molten metal through the gating system of the roller was due to the design of taper sprue and pressurized gating system. The molten metal enters to the mold through gate and rises almost uniformly in the cavity of the mold until it has completely filled up. This is a good filling because it ensures no sand erosion in the mould and solidification of liquid metal immediately starts in the mould cavity. Figure 4.14 clearly shows metal filling in mould cavity, that ensure the smooth flow of Liquid metal and the cold metal is not entering in the mould cavity. The pouring temperature for grey cast iron is 1300°C. The estimated pouring time for complete filling of mould cavity was 52.84 seconds. As per the simulation result it was observed that the cavity was filling smoothly, uniformly without any turbulence and temperature differences. Analysis in Filling was shown in figure 4.14 where in the uniform distribution of color suggests no presence of unwanted gases, slags, inclusions, dross etc. This indicates that a positive result of the casting simulation as riser was lately filled to compensate shrinkage in roller casting.

Figure 4.14 Temperature at filling time

4.10.2 Solidification time analysis

Solidification time is the time in seconds for each part of roller to become completely solid, which is from the pouring end time to the solidus point of time. Solidification time is proportional to volume to surface area ratio [47]. After a liquid metal has been poured in to the mould cavity, solidification of mill roller was started. Solidification in mill roller casting process is generally complex, where physical, thermal, and metallurgical phenomena take place simultaneously. To achieve the sound casting of mill roller, directional solidification is necessary. The directional solidification starts from thinnest section to thickest section and which ends at riser. Solidification is a result of heat transfer from internal casting to external environment. The heat transfer from the interior of the casting has to go through the various routes. The actual solidification of metal begins at liquids temperature of 1245°C. The solidification of metal ends at solidus temperature 1129°C. Figure 4.15 shows that the solidification time plots of directional solidification for the mill roller casting process, which is helps to locate the isolated areas of molten metal within the casting and gives a general idea of directional solidification in various areas of the mill roller. From graphical result, solidification time at different time steps was shown in various colors. Therefore, in the model volumetric shrinkage defects were occurred.

Figure 4.15 Solidification time of mill roller

4.10.3 Fraction solid time analysis

Critical fraction solid time is the time in minutes for a part of the roller casting to reach the critical fraction solid point, the point at which the molten metal loses its ability to flow liquid feed metal from the time the pouring ends. The fraction of solid and liquid metal in the mushy zone is a function of time and temperature. When the last drop of liquid metal is crystallized into solid, the solidification process is completed [47]. Temperature range at the start of mould filling to the end is same in mill roller and gating system. The simulation result indicated that directional solidification was occurred in mill roll casting process. Initially the mould cavity was filled with liquid metal, as the time passes the liquid metal was converting into solid when latent heat was released. At time step 0, fraction solid was zero that is pouring temperature (1300°C) and as time step passes latent heat was removed from metal and phase change was occurred. At time step 1 the whole model was completely solid. At step 1 the latent heat was removed from last of roller area. Fraction solidification situation are shown in in figure 4.16, the whole model is white in color that shows that roller is completely solid.

Figure 4.16 Fraction solid time of mill roller

4.10.4 Shrinkage porosity analysis

Shrinkage porosity defects are cavities inside components which can cause material weakening and if positioned on surface, can worsen aesthetic quality and corrosion resistance. Shrinkage porosity appears during material solidification phase, which begins with mould filling phase and ends when every part of the material is completely solidified. The cause of its creation is material shrink.

The shrinkage porosity was predicted with the computer simulations of the filling and solidification processes. The liquid metal was solidified when the heat present in it was released and change of phase is occurred from liquid to solid. As the result Shrinkage porosity were occurred in the mill roller casting process.

Shrinkage defects occur when feed metal is not available to compensate for shrinkage as the metal solidifies. If the shrinkage porosity is small in diameter and confined to the very center of thick sections it will usually cause no problems.

Figure 4.17 shows shrinkage porosity is present in the casting component simulation. It is observed that shrinkage porosities at riser and mill roller component. But in the simulation these shrinkage porosity present in the component are eliminated by providing appropriate gate and riser at the proper location, and also the increasing the height of riser.

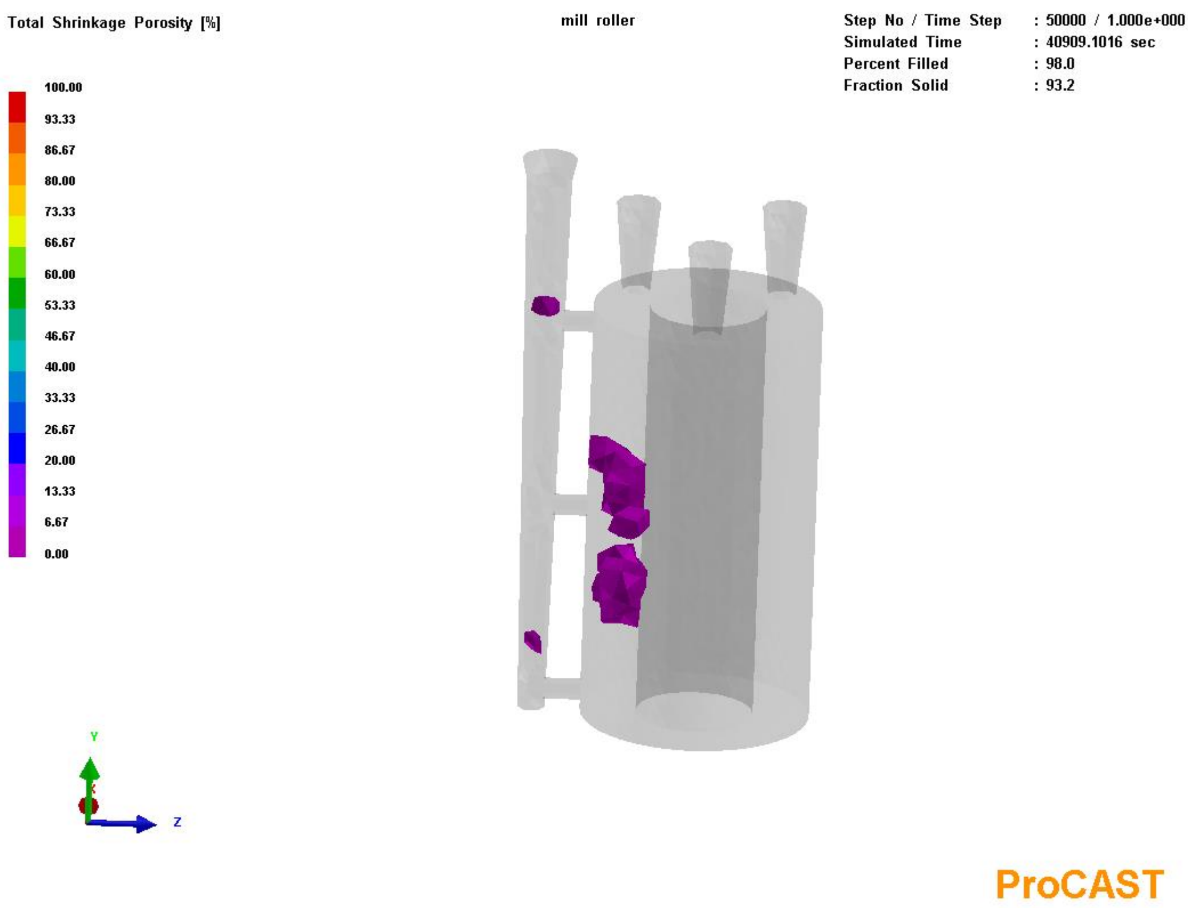

Figure 4.17 Total shrinkage of mill roller

CHAPTER FIVE

5. RESULT AND DISCUSSION

The case study was carried out on mill roller product from grey cast iron with $980mm \times 500mm \times 1840mm$ of outer diameter, inner diameter and height respectively. The model elements which were take account in the mill roller casting process were built using solidwork software. Then, all these elements were placed in with their respective positions and locations of the mold.

The numerical, experimental and simulation results obtained based on the available data were discussed with respect to the facts that occurred and compared to the literatures.

5.1 Discussion with numerical results

5.1.1 Clay content of molding sand used

From table 10 the clay content of molding sand used was determined experimentally and found as 6.88%. The sample sand clay content taken was compared with to the standards of foundries molding sands, "grade A" type sand having 5-10% of clay. In the literature as discussed that this sand has sintering (fusion) temperature resistance capacity of 1350-1450^{O}C, which is grater as compared to the pouring temperature of liquid metal used (1300 ^{O}C). Other cavity facing sand (dolomite powder) and paint element (Zirconium) was also used with the sand that has resisting capacity. Due to these materials the powering temperature of liquid metal has blocked and reduced in its power prior to heating of silica sand. As a result, sand sintering problem from this sand was not produced rather it used with old sand. In addition, the sand with this clay content has not muddy effect on mold and hence probability of porosity formation on the mill roller is less.

5.1.2 Grain Fineness Number (GFN) of moulding sand used

From Table 11 the GFN value of the molding mixed sand (new-sand mixed with reclaimed sand) used was determined experimentally and found as 50.81. This sand is fine grain sized sand compared to the standard GFN values of molding sands used in foundry technologies. According to this result, sand with such GFN values is highly compacted while mixed with resin and catalyst during mold making. Hence, a mold made from this sand was highly compacted. As a result, challenge of gas bubbles out from metal during solidification and caused to porosity formation in the roller casting.

During mill roller casting the utilization of resin and catalyst amount with sand in mold making can be caused to porosity formation. The mold made of compacted sand is less permeable due to high amount of risen whereas mold made of less amount of resin resulted to less strength. Whereas, mold made of high amount of catalyst can be hard caused challenge to gas out and small amount of catalyst lead to weak mold and caused sand erosion during metal pouring to the mill roller cavity.

5.1.3 Casting gross weight

Using the maximum yield of grey cast iron material, The gross weight of metal (9520Kg) was determined used to completely fill the given mill roller mold cavity and the gating system cavities which take part in mill roller casting. Based on the standard design considerations this designated weight was sufficient for the mill roller casting including the given shrinkage allowance, machining allowance and pattern allowances. Hence pattern size was enough to cast the required client's weight of 8106.1 kg and the designed net weight of 8568 Kg. The amount of metal weight accumulated in the mold cavity and gating system elements was equivalent to 9520 kg which is equivalent to the determined value. So, nothing left in the furnace that can be considered as wastage for a single roller. Ergo, 90% casting yield was enough that gives a gross weight of 9520 Kg to fill the total cavities which used in the mill roller casting.

5.1.4 Gating system elements

Based on the principle of pressurized gating area ratio rule applicable for grey cast iron castings, the overall sizes of gating system elements utilized in mill roller casting were designed and determined. The gating area ratio that take in mill roller castings were chock area and total ingate area with the exclusion of runner area because of vertical casting with side gating system. The gating areas ratio of grey cast iron was used in this thesis work "1: 1.1" respectively to chock area and total ingate areas. In the literatures seen that this may be give small sizes of the critical gating system dimensions as compared to the standard gating areas ratio of 2:1 that applied for grey cast iron castings. Therefore, small sizes of these gating system elements lead to turbulence flow condition within the channels (not necessary in castings) and cause for metal solidification before cavity filled and resulted to volumetric solidification shrinkage occurred in the mill roller.

5.1.5 Freezing periods of riser and mill roller

Based on riser and mill roller modulus ratio method, the freezing time or freezing ratio (RF) of riser to casting was determined using Equation (4.21) and found as 0.4469. This indicates that volume to area ratio of riser is 0.0476 and that of casting is 0.1065 and hence volume to area ratio of the riser is 0.4469 times greater to the volume to area ratio of the casting. Accordingly, the riser used freeze after completion of mill roller freezing by 0.4469 times later. Based on the modulus ratio method the riser design can be satisfactory for the given weight of mill roller to feed properly. Therefore, the riser used with the designed dimensions was satisfactory in producing a sound mill roller casting.

5.1.6 Riser feeding distance

By considering the height of the section being fed, the minimum feeding distance of the riser towards its opposite sides, along the height of the mill roller is 216 cm. The mill roller casting maximum diameter is 98 cm (Therefore the pattern diameter determined from machining allowance), the determined minimum feeding distance of riser (98cm) indicated that the minimum sections of the roller can be fed by it properly. Through constant thickness of the roller, the riser can be feed to the base of the roller which is near to its location first and then the metal accumulated in this section can be served as local riser that compensate metal shrinkage in the middle sections. Hence less probability of shrinkage formation in casting of mill roller and this riser was taken as an effective in feeding metal of the designed mill roller weight of 8568 Kg in the mold cavity.

5.1.7 Comparison of riser and mill roller solidification period

By Using Chvorinov's rule for cast iron castings, the total solidification times of both the riser and the mill roller were determined and found as 48 hours and 31.27 hours. Based on the experiment these results indicate that the total time taken of the molten liquid of the grey cast iron to solidify from the pouring stage to its solid to cooling completed stage. As a result, the riser used can be feed and compensate metal for the given weight and effective in producing sound mill roller castings with minimizing shrinkage, misrun and porosity formation. Hence the riser solidified after mill roller solidified.

5.1.8 Effect of pouring heads on mill roller casting

The high pouring head can be delayed the molten metal in air before entered to the pouring cup. Due to this effect air entrainment can occurred and the metal reduced its temperature. This reduction in temperature result to solidification before cavity filling and hence misrun can occurred in the mill roller casting. Large pouring head can also induced high velocity flow of metal that causes mold erosion in the sprue entrance. This leads either to close the lines of a metal flow or entered to the mold cavity and became part of the casting. This causes formation of poor surface roughness and sand sintering which is difficult to machining. Short pouring head can also reduce air entrainment, solidification of metal, but cause over flow in the gating system particularly in ingate of mold cavity. As a result, formation of turbulence flow in the mold channel occurred and produced mill roller with high surface roughness.

5.1.9 Effect of pouring velocities in mill roller casting

The metal flows into the down sprue increases in its velocity for pressurized type of gating system used. Hence the cross-sectional area of the channel is tapered. Therefore, volumetric flow rate of the metal in the channels (top and bottom of sprue) can be remains the same. As the sectional area of sprue increases or remain constant towards the sprue base cross sectional area, air can be aspirated in to the liquid and taken in to the mould cavity. To avoid the effect the sprue area can be made in taper shape and believed that air aspiration during mold filling may not be occurred in the production of mill roller.

In mill roller casting, the velocity and flow rate results do not indicate the fluid flow condition that occurred within the channels of gating system used. From Reynold's numbers (Re) predicted that the type of fluid flow that occurred (turbulent) in the mold channels using Equation (4.25) from the respective hydraulic diameters. The Reynold's number (Re) results in the circular (sprue entrance and exit) and rectangular (ingate) sections are 43,292, 59,539.76 and 43,954.47 respectively.

Table 5.1 Summery of metal flow and velocity results

Parameter	1	2	3
Area (m^2)	0.0078529	0.0059459	0.00156658
Velocity (m/sec)	0.97	1.28	1.77
Flow rate (m^3/sec)	0.0076096	0.076096	0.0076096
Re	43,292	59,539.76	43,954.47

Table 5.1 shows an increment of metal flow for the velocity results, except in ingate section. This result indicates that liquid metal with a maximum velocity of 1.77 m/sec and flow rate of 0.0076096 m^3/sec was entered to the mill roller mold cavity and caused to unwanted flow in the channels. The actual metal speed in the channels considered as less than the above determined results due to the fact that surface tension effect and other factors of the mold was not considered.

In Table 5.1 the Reynold's number (Re) results predict that the fluid flow condition was turbulence flow within the hydraulic diameter of the channels. The channel surface tension effects on flow retardation, the actual flow results can be less than from what are found using Equation (4.25). Along the channels the flow also reduced (damped) as both viscosity and density of metal increased. Therefore, due to the (and other) factors the actual metal flow entered to ingate can be less flow condition (turbulence type of flow). As a result, flow in the channels could faster fluid flow at the center than fluid flow towards the edge of the stream.

So, friction occurred between layers within the fluid (instability flow of molecules) and caused for the formation of rough surface on the mill roller casting.

5.1.10 Temperature loss in gating system

According to the design used in mill roller casting the amount of temperature loss to the gating system elements after pouring completed is 0.485℃. This result indicates temperature of the molten metal was reduced by 0.485℃ along the channel prior to enter the mold cavity. Hence, the liquid metal entered to the mill roller mold cavity was with a temperature of approximately 1299.52℃. In addition, one of the best behaviors of grey cast iron material is slow solidification rate after melting. Hence, the metal cannot be further decreased throughout the height of the mill roller mold cavity before pouring completed. As a result, lack of the metal fluidity cannot be occurred which caused to shrinkage formation and initiation of misrun in mold cavity of the mill roller.

5.1.11 Molten metal refining and metal additives used

Based on the amount of gross weight of metal to casted the amounts of deslagging agent of 5kg were added to the metal during melting. Pouring impurities like gas bubbles (carbon mono-oxide) and oxygen gas present within the molten metal may be removed and out. The impurities can be collected at the top surface of the molten and remove out using sticks manually by the operator after added the deslagging agent. Hence the collected impurities cannot be fully removed and poured along with metal in to the mold channels. As a result they have little an effect of solidification before cavity completely filled but due to slow solidification rate behavior defects like misrun cannot be occurred in mill roller casting.

5.2 Discussion of experimental results

Design of experiment (Taguchi's method) was applied to set appropriate process parameters of the selected mill roller products of the company casting process. Three process parameters at different levels were taken for mill roller product. Three levels (low, medium and high) were allocated for each control factors of mill roller product depending up on the data collected from the company casting department. According to the number of factors and their respective levels experimental run has undertaken. After all the experiment was analyzed using Minitab 17 software in which L9 orthogonal arrays were used. Mean response, S/N ratio and graphical main effect plot of S/N ratio and means were stored in the worksheet of the analysis process. Detail analysis was done on the mean response and S/N ratio of each experimental run of the product. ANOVA analysis was also done for mean response table and

S/N ratio table for mill roller product to identify which factor setting is most significantly affecting the response value so that its factor setting is considered in emphasis.

5.2.1 Signal-to-noise [S/N] ratio results

In this study, mill roller defect due to sand casting was considered as the main characteristic. Mintab-17 software was used to calculate the influence of process parameters on mill roller due to casting defects response. In order to assess the influence of factors on the response, the mean and the Signal-to-noise ratio for each control factor was calculated and represented in table 4.11. The decisive factor - 'smaller is better' was used for choosing the S/N ratio. The response table for S/N ratio was shown in the tables 4.12.

Figure 4.11 represent the main effect plots for S/N ratio of mill roller casting defects. From this table and figure, it can be concluded that Permeability of sand mold is the most influential factor for changing the percentage of casting defects and moisture Content has less effect. Mill roller defect is Minimum in third level of permeability (145), third level of pouring temperature (1300℃) and second level of moisture content (2.5%) from main effects plot of both mean values and S/N ratios respectively.

5.2.2 Analysis of variance (ANOVA) test results

Analysis of variance is one of the most commonly used statistical tools for determining the percentage contribution of each parameter in any process analysis. In this study grey cast iron sand casting was performed for making cast iron mill roller component in Akaki Basic Metals Industry foundry and the factors which are responsible for casting defects was found by using this analysis of variance method. Mintab-17 software was used to calculate the percentage contribution of each process parameter to the overall casting defects. Table 4.13 shows the results obtained using analysis of variance for S/N ratios for mill roller casting defects. In this investigation, the results acquired from the analysis of variance process implies that the permeability has majority of percentage contribution for the casting defects of about 61.35 % , poring temperature 21.64% and moisture content 2.95 % in mean values and S/N ratios sequentially.

5.3 Confirmation of experimental results

The confirmation experiment was used to determine that the selected control parameters values produce better results than those produced in the conventional experiment. Total 4 confirmation experiments were conducted in foundry shop at the optimal settings of the process parameters which is shown in table 4.16. The average of the defects for mill roller casting value is 8.6 %. But in conventional method the percentage of defect for casting mill roller was 9.36 %. So it can be declared that the selected parameters with their levels are significant enough to obtain the desired result.

5.4 Discussion of casting simulation results

ProCAST is a modular system and allows the coupling of various modules. Based on Finite Element technology, ProCAST provides a complete solution covering a wide range of simulation. 3D models of the casting has prepared with all the gating and risering system by using solidwork software. The solid modeling of mill roller component with gating system is under taken by solidwork software then the file is saved in IGES file format. The different input materials properties and conditions used in casing simulation processes were given in table 4.17. Figure 4.12 indicates the meshed geometry of the mill roller which was done using the meshing operation. The mill roller was meshed using defined small element size (fine) that it can be give the more accurate simulation results as compared to large element size (default case and coarse). So, visual mesh operation of 2D surface mesh and 3D volume mesh was performed for the roller simulations. Due to the design of taper sprue and pressurized gating system, the molten metal enters the mould through gate and rises almost uniformly in the cavity of the mould until it has completely filled up. This is a good filling because it ensures no sand erosion in the mould and solidification of liquid metal immediately starts in the mould cavity.

5.4.1 Filling process analysis result

In a filling process Mathematical modeling and simulation of conservation of mass, momentum, and energy provides information about velocity of molten material within the mold cavity, the direction of flow, and temperature and pressure at various instances within the mold. Simulation results provide information about filling of molten metal in the mold, solidification behavior, quality, and defects of the mill roller cast products. Based on the result, the cavity of roller fill without turbulence occurs this is due to the design of taper sprue and pressurized gating system. The molten metal enters the mould through gate and rises almost uniformly in the cavity of the mould and completely filled up. This is a good filling because it ensures no sand erosion in the mould and solidification of liquid metal. The pouring time to complete mold cavity filling is 52.84 seconds.

The simulation results shows that metal filling in the mould cavity is smooth flow of Liquid metal and the cold metal is not entered in the mould cavity. Analysis of filling is shown in figure 4.14, where filling smoothly, uniformly without any turbulence and temperature differences and uniform distribution of color suggested that no presence of unwanted gases, slags, inclusions, dross etc. Hence, defects like sand erosion and air entrapment is not occurred.

5.4.2 Solidification time analysis results

Casting solidification helps to view the cooling process from exterior casting surface to interior, and to detect the location of shrinkage porosity. Solidification time Simulation results are shown in figure 4.15. Solidification is started after the liquid metal is poured and directional solidification is started from thinnest section to thickest section and which ends at riser. There temperature variation in the modeled mill roller part during solidification. The solidification of mill roller metal is started at liquids temperature of 1245°C and The solidification of mill roller metal ends at solidus temperature 1129°C. During solidification process latent heat is removed from the cast and then the cast is completely solid. The directional solidification started from thinnest section of the part to thickest section of the part and then which ends at riser. Figure 4.15 shows that the solidification time plots of directional solidification for the mill roller casting process, which is helped to locate the isolated areas of molten metal within the casting and gives a general idea of directional solidification in various areas of the mill roller. The solidification time at different time steps were shown in various colors was given graph and the change in liquid phase to solid phase was easily found.

5.4.3 Fraction solid analysis result

The fraction of solid and liquid metal in the mushy zone is a function of time and temperature. Temperature at the mould filling and end of pouring s the same, this indicated that no inclusion of air entrapment, slag, sand and other defects. Based on the simulation result, directional solidification is occurred in mill roll casting process. These situations are shown in figure 4.16. Initially the whole model is filled with liquid and as the time passes the liquid metal was converting into solid as latent heat is released. At time step 1 the model is completely solid. At step 1 the latent heat is removed from last of roller area

5.4.4 Shrinkage Porosity analysis result

Shrinkage porosity shows areas where the ratio of voids to total volume is greater than or equal to the specified percentage value. Shrinkage porosity appears during material solidification phase, which begins with mould filling phase and ends when every part of the material is completely solidified. The cause of its creation is material shrink. The most common cause of shrinkage is related to the casting sprue, which is the passage through which molten material is poured in to a mold.

Shrinkage cavity is predicted with the computer simulations of the filling and solidification processes of mill roller casting. As metal solidify it is going to change phase from liquid to solid and going to shrink so the compensating liquid metal available from riser. Shrinkage defects occur when feed metal is not available to compensate for shrinkage as the metal solidifies. If the shrinkage porosity is small in diameter and confined to the very center of thick sections it will usually cause no problems. Figure 4.17 indicates that shrinkage porosity is in both riser and roller part occurred this is due to slow solidification rate of grey cast iron.

CHAPTER SIX

6. CONCLUSSION, RECOMMENDATION AND FUTURE WORK

6.1 Conclusions

The feasibility of using statistical techniques for minimizing sand cast mill roller defects has been proved successfully. Table 4.12 clearly shows that almost all the parameters affect both the mean and variance of the casting defects.

Based on the experiment and simulation analysis the following conclusion is drawn.

1. The application of Taguchi's method to the mill roller sand casting process used to:
    - ✓ Improve the productivity of the mill roller.
    - ✓ Increases stability of the casting process of mill roller.
    - ✓ Mill roller A higher yield is possible
2. The casting defects in the mill roller are 6.17% of the castings produced, and, after the application of Taguchi's method, the casting defects are reduced to a maximum of 3.19 % of the total castings produced.
3. From the design of experiment, the process parameters of the sand casting mill roller optimum factors and levels are identified. The optimum factors and levels are permeability 145 (No); pouring temperature 1300℃ and moisture content 2.5%.
4. The percent contribution of each factor is also determined and found as permeability 61.35%, pouring temperature 21.64% and moisture content 2.95% and the improvement in minimizing the casting defects of mill roller was 48.29 percent.
5. The numerical calculated results have shown that the misrun and volumetric solidification shrinkage defects occurred in the mill roller castings were due to the improper utilization of patterns of the gating system elements.
6. Casting simulations are capable of examining the effects of several casting parameters such as total solidification time, fill time and mold configuration in producing sound castings. The accurate prediction of these defects at design stage can greatly help in providing sound casting to reduce casting defects in mill roller.
7. The experimental results have shown that the sand sintering problem and porosity defects occurred in the mill roller castings were due to the weak sintering strength of fine mixed molding silica sand used in casting process of the roller in the foundry industry.
8. It can be concluded that simulation helps to visualize filling and solidification phenomena with no wastage of time, energy, labor and money. The simulation results

have shown that volumetric solidification shrinkage and porosity defects occurred in the roller castings.

6.2 Recommendation

According to the results observed for the mill roller casting in ABMI foundry the following recommendation forwarded:

1. Some machines of the company are too old and almost obsolete, should have to replace with the advanced one.
2. Should prepared and used patterns of gating system for the mill roller with actual size
3. The chemical composition of grey cast iron should be kept with the customer specification.
4. Strongly recommend the company to use and apply Taguchi's method of design of experiment.

6.3 Future work

From the study being conducted it has observed that design of experiment is a powerful tool in optimization of process parameter mill roller casting. Taguchi's method of design of experiment is applied successfully for the optimization of control factors for performance parameter of a given product. Fuzzy logic coupled with Taguchi method research areas were recommended to be undertaken in the future that can be used in the optimization of multiple response parameters.

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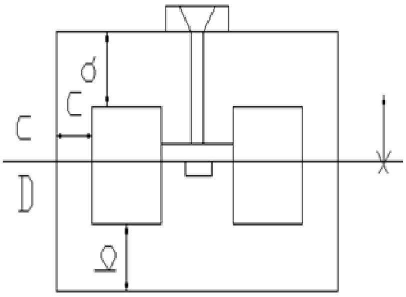
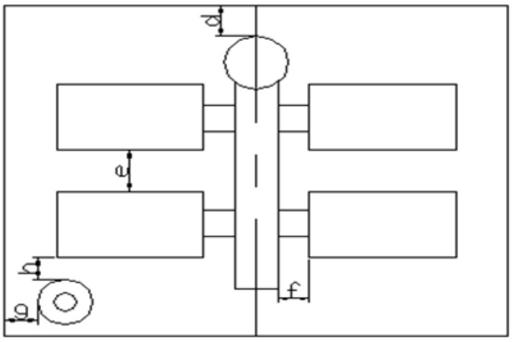
APPENDIX A

Appendix A: CLEARANCES DATA BETWEEN CASTING AND FLASK

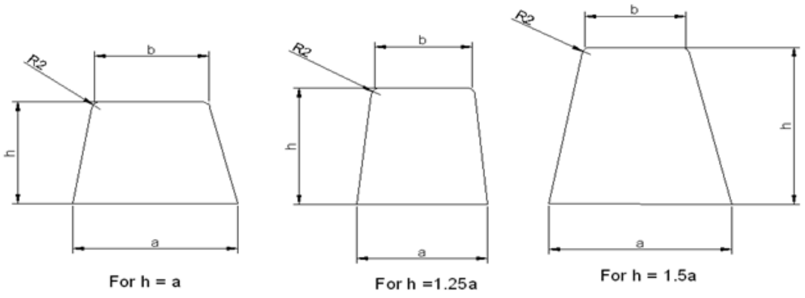




Weight of casting in kg	*Determining dimensions*							
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
To5	*40*	*40*	*30*	*40*	*30*	*20*	*20*	*20*
5-10	*50*	*50*	*40*	*40*	*40*	*25*	*25*	*25*
10-25	*60*	*60*	*40*	*50*	*40*	*30*	*25*	*25*
25-50	*70*	*70*	*50*	*60*	*50*	*40*	*35*	*35*
50-100	*90*	*80*	*60*	*70*	*60*	*50*	*40*	*40*
100-250	*100*	*90*	*70*	*80*	*70*	*60*	*50*	*50*
250-500	*150*	*150*	*90*	*90*	*90*	*70*	*50*	*50*
500-1000	*200*	*200*	*100*	*100*		*120*	*100*	*100*
1000-2000	*250*	*250*	*125*	*125*		*150*	*100*	*100*
2000-3000	*300*	*300*	*150*	*150*		*200*	*100*	*100*
3000-4000	*300*	*300*	*200*	*200*		*225*	*150*	*150*
4000-5000	*350*	*350*	*250*	*300*		*250*	*200*	*200*
5000-10000	*400*	*400*	*300*	*350*		*300*	*200*	*200*

APPENDIX B

Appendix B: RELATIONS BETWEEN INLET SIZE AND LENGTH OF INGATE



	For h=a			For h=1.25a			For h=1.5a		
$A(cm)^2$	a	b	h	a	b	h	a	b	h
1.0	11	8	11	-	-	-	-	-	-
1.3	12	10	12	11	8	14	-	-	-
1.6	14	10	14	12	9	15	11	7	17
2.0	15	12	15	14	10	17	12	8	20
2.5	16	13	17	15	11	19	14	10	21
3.15	18	14	19	16	12	21	15	11	23
4.0	22	18	21	18	13	25	18	14	26
5.0	24	19	24	22	16	27	20	15	30
6.3	26	21	27	24	18	30	23	16	34
8.0	30	27	30	26	19	35	24	17	38
10.0	34	28	33	30	22	38	28	20	42
12.5	38	30	37	36	26	43	30	22	47
16.0	42	31	42	38	29	48	36	23	54
20.0	48	38	47	42	32	53	40	28	60
25.0	52	42	53	48	36	60	44	32	66
31.5	60	48	59	52	40	65	50	33	73

APPENDIX C

Appendix C: ORTHOGONAL ARRAY SELECTOR [49]

	Number of Parameters (P)																													
Number of Levels	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

APPENDIX D

Table D.1: Data related with yield of casting alloys,[35]

Item	Steel	Grey cast iron	Cast iron
Yelid %	40-60	80-90	75-80
Density kg/m^3	7860	7870	7870

Table D.2: Thermo-physical properties of molten grey cast iron [48]

Temperature ^{0}C	**Density Kg/mm^3**	**Specific heat (Cp) KJ/Kg ^{0}C**	**Thermal conductivity(K) W/mm ^{0}C**	**Enthalpy J/Kg**
1400	6756	0.8	20	1250
1300	6802	0.8	19	1150
1200	6849	0.8	35	1000
1100	6896	0.8	37	700
800	7037	0.8	41	520
600	7131	1.2	42	350
400	7225	0.9	45	210
200	7366	0.5	50	100

Table D.3: Thermal properties for casting materials [50]

Material	Specific heat, Cp (J/gOC)	Density ρ (Kg/m3)	Thermal conductivity K(W/m.OC)
sand	1.16	1500	0.60
Plaster	0.90	1.1	0.34
Mullite	0.77	1.6	0.37
Iron	0.70	7.9	73
Aluminum	0.90	2.7	202
copper	0.39	9.0	385
Magnesium	1.07	1.7	156

Table D.4: Thermal properties of mold and chill materials at approximately 20^{O}C [51]

Materia	Heat diffusivility , √(KρC) (J/m2Ks1/2)	Thermal deffusivility (K/ρC), (m2/s)	Heat capacity per unit volume (ρC), (J/Km3)
Silica sand	3.21 x10^{3}	3.60x10^{-9}	1.70 x10^{6}
Investment	2.12 x10^{3}	3.17 x10^{-9}	1.20 x10^{6}
Plaster	1.8 x10^{3}	3.79 x10^{-9}	0.90 x10^{6}
Iron (pure)	16.2 x10^{3}	20.3 x10^{-9}	3.94 x10^{6}
Graphite	22.1 x10^{3}	44.1 x10^{-9}	3.33 x10^{6}
Aluminum	24.3 x10^{3}	96.1 x10^{-9}	2.48x10^{6}
Copper	37.6 x10^{3}	114.8 x10^{-9}	3.60x10^{6}