



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

POROSITY EFFECT ANALYSIS ON THE DIMENSION OF CAST
PINION GEAR, DRIVE DISC AND HEAD STOCK COMPONENTS OF
MANGANESE STEEL

A CASE STUDY AT AKAKI BASIC METALS INDUSTRY

BY
NETSANET DESALEGN MOLALIGN

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitled “Porosity effect analysis on the dimension of cast pinion gear, drive disc and headstock components of manganese steel, a case study at Akaki Basic Metal Industry” is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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ABSTRACT

Production of parts by casting operation involves various processes which include pattern making, mold preparation, core making, melting and pouring, removal of the cast from the mold, cleaning, finishing and inspection. Defects in castings may occur during these processes due to some reasons. This study has been carried out mainly on porosity defects of manganese steel castings.

Porosity is one of the main challenges in steel castings at Akaki Basic Metals Industry. The problem occurs on the 4784kg of pinion gear, 900kg of drive disc and 4538 kg of headstock components of manganese steel castings. For the purpose of avoiding pores and cavities, large amount of material is removed from the surface of the steel castings by machining and grinding operations. This leads to rejection of the products due to unsatisfactory design requirements, or assembling defective components shortens the service life of the product for its intended purpose. The method used in the study includes physical observations, photographic analysis and experimental analysis by taking measurement of depth of pores and cavities. Data was gathered from both primary and secondary sources. The result of the experiment was analyzed using control charts and Ishikawa (cause and effect) diagram. Depending on the analysis results, interpretation was made and the root causes of porosity were identified and remedial actions required to improve the quality of steel castings with regard to the selected defective components are presented. Mold preparation problems, molding material property, pouring temperature and time, poor gating system design, inappropriate material composition and improper utilization of reclaimed sand are the main causes for porosity.

Experimental analysis implies that the maximum pore depths on the drive disc, pinion gear and headstock components are found as 24mm, 23mm and 24mm respectively. Removing these amounts of material from the finished surfaces highly reduces the desired dimensions of the parts. So the quality level of the components is taken as a reject due to unsatisfactory design requirements and the rework cost is high; 25,821.50 USD. Better combination of the process parameters like sand binder ratio, grain fineness number, mold permeability, proper gating system design, pouring temperature and time are the leading parameters to reduce the casting defects.

TABLE OF CONTENTS

	Page
AKNOWLEDGEMENT.....	iii
ABSTRACT.....	iv
LIST OF FIGURES.....	viii
LIST OF TABLES.....	ix
LISTS OF SYMBOLS AND ABBREVIATIONS.....	x
CHAPTER ONE:INTRODUCTION.....	1
1.1 Background of the study.....	1
1.2 Statement of the problem.....	4
1.3 Objectives of the study.....	4
1.4 Significance of the Study.....	5
1.5 Scope.....	5
1.6 Limitations.....	6
CHAPTER TWO: LITRATURE REVIEW.....	7
2.1 Casting process.....	7
2.2.1 Molding and core making in sand casting.....	9
2.2.2 Casting design.....	18
2.2.3 Melting practice.....	23
2.2.4 Pouring.....	24
2.2.5 Solidification.....	25
2.2.6 Cleaning and inspection of castings.....	29
2.2 Casting defects.....	29
2.2.1 Classification of casting defects.....	30
2.2.2 Defect analysis in steel casting.....	33
2.3 Porosity Defects in metal castings.....	34
2.3.1 Classification of porosity defects.....	35
2.3.2 Formation of shrinkage porosity.....	36
2.3.3 Porosity Sources.....	39
2.3 4 Causes of blow holes and pin holes.....	40

2.4 Summary of casting defects.....	41
2.5 Quality in casting.....	45
2.5.1 Casting quality assessment tools.....	46
2.5.2 Inspection.....	48
2.5.3 Major factors exerting influence on quality of steel castings.....	48
2.6 Porosity prediction in steel castings.....	51
2.7 Porosity control and reduction methods.....	54
2.8 Porosity analysis methods.....	54
 CHAPTER THREE: MATERIALS AND METHODS.....	 56
3.1 Materials.....	56
3.2 Methods.....	56
3.3 Equipment, machines and tools.....	56
3.4 Samples and sample preparation.....	57
 CHAPTER FOUR: DATA COLLECTION AND ANALYSIS.....	 59
4.1 Background of Akaki Basic Metals Industry.....	59
4.2 Molding methods and materials.....	66
4.2.1 Sand used at Akaki Basic Metals Industry.....	66
4.2.2 Binders.....	68
4.2.3 Proportion and Calibration of chemicals.....	69
4.3 Melting procedure.....	69
4.3.1 Melting furnaces.....	69
4.3.2 Deoxidation and tapping.....	70
4.3.3 Pouring temperature.....	71
4.3.4 Solidification time and temperature.....	71
4.4 Casting design.....	72
4.4.1 Riser design for the pinion gear.....	72
4.4.2 Gating system.....	74
4.5 Effect of pore sizes on the dimension of the pinion gear,.....	76
drive disc and headstock components	

4.6 Photographic analysis.....	77
4.7 Construction of the U-Chart.....	84
4.8 Cost analysis for rework of defective components.....	88
CHAPTER FIVE: RESULT AND DISCUSSION.....	91
CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS.....	103
6.1 Conclusions.....	103
6.2 Recommendations.....	104
6.3 Future research area.....	104
REFERENCES	106
ANNEXES.....	109
Annex A: Pattern allowances.....	109
Annex B: Average grain size based on grain fineness number.....	109
Annex C: Comparison of properties of no-bake binder systems.....	110
Annex D: Bubble size of entrained air adjusted for depth and temperature.....	110
Annex E: Thermo-physical properties of steel and heat transfer coefficients.....	111

LIST OF FIGURES

Figure 1: Basic production steps in sand casting process.....	7
Figure 2: Effect of catalyst addition on the setting time of typical furan type..... cold set resin bonded sands	14
Figure 3: Effect of percentage catalyst on the green compression strength..... development of typical furan type cold set resin bonded sands	15
Figure 4: Effect of temperature and furfural alcohol on viscosity of furan resins.....	15
Figure 5: Effect of sand temperature on the setting time of a typical furan..... type cold set	16
Figure 6: Effect of time after mixing before compacting on the compression..... strength of typical furan type cold set resin	16
Figure 7: Relationship between bench life, setting time and curing time..... for a typical furan type cold set resin bonded sands	17
Figure 8: Principal features of a gating system.....	22
Figure 9: Variations in gating position.....	22
Figure 10: Causes of blow holes and pin holes.....	40
Figure 11: Sectional front view of the drive disc selected for analysis.....	58
Figure 12: Schematic diagram of the pinion gear selected for analysis.....	58
Figure 13: Organizational structure of ABMI.....	63
Figure 14: Schematic diagram of a cylindrical riser.....	73
Figure 15: Schematic diagram of the gating system.....	74
Figure 16: Photographs of the defective drive disc sample selected for analysis.....	79
Figure 17: Photographs of the defective headstock samples selected for analysis.....	79
Figure 18: Photographs of the defective pinion gear sample selected for analysis.....	80
Figure 19: Depth of pores.....	83
Figure 20: Diameter of pores.....	83
Figure 21: U- chart for nonconformities in pore depths.....	87
Figure 22: U- chart for nonconformities in pore diameters.....	88
Figure 23: Cause and effect diagram of porosity.....	91

LIST OF TABLES

Table 1: Comparison of foundry base sands..... 11

Table 2: Relationships between the type of furnace and..... 24
the alloy type it is most suited for melting

Table 3: Flask opening time after pouring (for steel)..... 27

Table 4: Casting defects..... 31

Table 5: Possible causes for casting defects..... 32

Table 6: Various casting defects and their causes..... 42

Table 7: Annual production capacity of ABMI for selected products..... 62

Table 8: Materials used in steel casting..... 64

Table 9: Melting furnaces at ABMI and their capacity..... 69

Table 10: Some dimensions and pore depths of the pinion gear, drive disc..... 77
and headstock components

Table 11: Various pores sizes..... 82

Table 12: Data for Nonconformities in pore depths..... 85

Table 13: Data for Nonconformities in pore diameters..... 86

Table 14: Material cost for rework of the selected defective components..... 89

Table 15: Tools and equipment cost..... 89

Table 16: Labor cost..... 89

Table 17: Summary of rework cost..... 90

Table 18: Maximum pore depths on the selected defective components..... 98

ABBREVIATIONS

ABMI	Akaki Basic Metal Industry
AFS	American Foundry Society
ANSI	American National Standards Institute
ASQC	American Society of Quality Control
BMEC	Basic Metals and Engineering Corporation
CAD	Computer Aided Design
CL	Center line of control chart
DPPC	Design, Production, Planning and Control
FA	Furfural alcohol
FWS	Foundry Workshop
GFN	Grain fineness number
HCF	Hand tools, Cutlery & Forging
HM	Hand Molding
HST	Heat and Surface Treatment
JCFS	Japan Casting Foundation Society
LCL	Lower Control Limit
MM	Mechanized molding
MWS	Mechanical Workshop
NDE	Nondestructive testing
U-Chart	Control chart for Nonconformities
UCL	Upper Control Limit

LISTS OF SYMBOLS

$\hat{\sigma}$	Standard deviation
A_i	Ingate (chock) area
C_H^0	Initial gas concentration within liquid
d_c	Dendritic cell spacing
D_n	In gate diameter
e	Eutectic phase
f_l	Mass fraction of liquid
f_s	Mass fraction of solid
g_g	Volume contraction of gas
g_l	Volume contraction of liquid
g_s	Volume contraction of solid
g_{se}	Volume fraction of solid eutectic
h_g	Intrinsic enthalpy of gas
h_l	Intrinsic enthalpy of liquid
h_s	Intrinsic enthalpy of solid
K_{eff}	Effective thermal conductivity
L_n	Length of in gate neck
P_b	Pressure of gas-forming bubble
P_f	Final temperature
P_{Hd}	Pressure inside the liquid
P_i	Initial temperature
S_4	Correction factor for pouring time calculation
t_f	Solidification time
T_f	Final temperature
T_i	Initial temperature
V_f	Final volume
V_i	Initial volume
μ	Absolute/ dynamic viscosity of a fluid
ρ_{se}	Density fraction of solid eutectic

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

The advancement of economy and civilization of the country today is directly or indirectly based on manufacturing of goods and products including textiles, metals, plastics, ceramics etc. Casting is the process in which the molten metal (of which the component is to be made) is poured in a mold (cavity) and allowed to solidify. The molten metal on solidification gets the shape of the mold. The mold has the shape of the job. Hence the metal is cast to the shape of the job. The mold or cavity, in which the molten metal is poured, is made with the help of the pattern [1].

Molten metal poured in to a mold flows in to the corners and fill all the voids. When metal solidifies, it takes the shape of the mold but not exactly the same because solid being denser there is reduction of volume from 2 to 9% [2]. The major characteristics which determine the place of casting in engineering includes: size, complexity, weight saving, production prototypes and wide range and versatility [3].

The term casting is also applied to the part that is made by this process. It is one of the oldest shaping processes, dating back 6000 years. The principle of casting seems simple: melt the metal, pour it into a mold, and let it cool and solidify; yet there are many factors and variables that must be considered in order to accomplish a successful casting operation. A variety of shape casting methods are available, thus making it one of the most versatile of all manufacturing processes [4]. Among its capabilities and advantages are the following:

- Casting can be used to create complex part geometries, including both external and internal shapes;
- Some casting processes are capable of producing parts to net shape. No further manufacturing operations are required to achieve the required geometry and dimensions of the parts. Other casting processes are near net shape, for which some additional shape processing is required (usually machining) in order to achieve accurate dimensions and details;
- Casting can be used to produce very large parts. Castings weighing more than 100 tons have been made;
- The casting process can be performed on any metal that can be heated to the liquid state;

- Some casting methods are quite suited to mass production.

There are also disadvantages associated with casting. These include limitations on mechanical properties, porosity, poor dimensional accuracy and surface finish for some casting processes, safety hazards to humans when processing hot molten metals, and environmental problems.

Parts made by casting processes range in size from small components weighing only a few ounces up to very large products weighing tons [4].

Metal casting is one of the direct methods of manufacturing the desired geometry of an engineering component by pouring molten metal into a mold within which the metal subsequently solidifies. The method is also termed as a near net shape process. A number of materials, pieces of equipment and processes are employed in the production of such a cast product. The occurrence of defects in castings can be attributed to many causes, e.g. the influence of design, process and material parameters or the equipment employed. This complexity makes the defect analysis more of an art-based on experience than an in-depth scientific analysis.

Metal founding is one of the oldest of all industries which stayed dated back to the dawn of civilization. Even in pre-historic times, as far back as 5000BC metal objects in the form of knives, coins, arrows and household articles were in use. Copper and bronze were common in ancient times but evidence indicates that iron also had been discovered and developed in the period around 2000BC, though its use was greatly restricted. Around 500 BC started the era of religious upheavals, and metals began to be used for statues of gods and goddesses. Bronze was still the most popular metal. Since Alexander was contemplating victory over the Eurasian continent the whole art of metal founding has emerged as an exact science [1, 3, 5].

Amongst the earlier scientists the work of Reaumur (1683-1757) is of outstanding interest to foundries. In the course of wide ranging activities he became interested in cast iron: not only this he produce malleable iron but he showed a clear perception of the range of cast iron structures and of the factors influencing the production of white, grey and mottled irons. Despite the interest of a few early scientists, metal casting was looked up on as an art and this view persisted until well in the 20th century. Many foundries sprang up after the industrial revolution, the vast majority being for the manufacture of the cast iron then being used as a structural material. The original industry grew around the skills of the molder and the pattern maker, craftsmen in the

direct tradition of earlier masters of the art of casting. However, the enhancement of the metallurgical quality and soundness awaited later scientific understanding and the advent of non-distractive testing. Hence, the quality production of iron castings in the 19th century was not matched a universal advance in quality and the engineering use of the products encountered risks that were the more series in a non-ductile materials [3,5].

Metal casting is unique among metal forming processes for a variety of reasons. Perhaps the most obvious is the array of molding and casting processes available that are capable of producing complex components in any metal, ranging in weight from less than an ounce to single parts weighing several hundred tons. Casting processes are widely used to produce metal parts in a very economical way, and to obtain complicated shapes with minimal machining for intended end use. It is unavoidable that many different defects occur in casting process. Casting as a manufacturing process to make complex shapes of metallic materials in mass production may experience many different defects such as porosity, shrinkage, blowhole and incomplete filling [6].

Due to various reasons, the cast product may have defects which may cause its rejection. The defects may be minor, intermediate or major. The castings having minor defects can be economically and readily repaired. The castings having intermediate defects may result in high cost of repair but the casting may be usable. The castings having major defects are scrapped. Factors for defective castings may include: defective pattern design, defective core making and molding equipment, improper core material, improper mold material composition, improper placement of gating and risering, non-optimal temperature of the molten metal, improper handling of the equipment and lack of experience of the foundry men [1, 2, 3, 5]. A cast spares without defects means a spare which is used for the maximum endurance time so that down time of machineries are minimized, resources are saved and productivity is increased.

The defective components selected for this study; the pinion gear, drive disc and headstock components are made of manganese steel. The intended purpose of these products includes carrying of very huge metallic components and power transmission by driving other driven parts. To give the desired services the parts be free of defects. Though good quality is required, the selected components contain different casting defects. These defects include porosity, shrinkage cavity, sand sintering and cracks. Porosity is the main concern in this study and the level of

porosity on the selected components is very severe. This leads to rejection of parts and the industry is spending much amount of money for rework of the defective components. The study brings an overview of casting defects and major activities to improve quality of steel castings. Advances in the prominent casting quality assessment tools and techniques of control charts for number of demerits per unit (U- charts) and cause and effect (Ishikawa or fishbone) diagram are then presented.

1.2 Statement of the problem

The products from the foundry shop of Akaki Basic Metals Industry are the large input materials for the rest of the workshops in the industry. Almost 100 percent of the products of the industry are manufactured by casting process; meaning, the purpose of establishing the industry is to produce spare parts and machinery components by casting process. Though the foundry shop is the very important shop at Akaki Basic Metals Industry, it is suffering from casting quality related problems. Most of the problems which exist in the foundry section, especially in steel castings of the industry include high defects and reworks, high rejections, high production cost, loss of customers and limited market competition. Porosity is one of the main challenges at Akaki Basic Metals Industry. Blow holes, sand inclusion, sand burning, cracks, hot tears, surface cracks, pin holes and shrinkage cavity are the other defects appear in cast iron and steel castings of the industry. For the purpose of avoiding pores and cavities, large amount of material is removed from the surface of the steel castings by machining and grinding operation. This leads to rejection of the product since it is below the specified dimensions in the design analysis of the component.

On the other hand assembling defective components may shorten the service life of the product for its intended purpose due to unsatisfactory design requirements. Therefore minimization of casting defects is very important for improved productivity of the industry by identifying the root causes and giving possible remedies of porosity defects.

1.3 Objective of the study

General objective

The general objective of the study is porosity effects analysis on the dimension of cast pinion gear, drive disc and head stock components of Manganese steel for steel casting quality improvement at Akaki Basic Metal Industry.

Specific objectives

- Identifying the causes of porosity defect in steel castings of the industry;
- Categorizing the causes of porosity casting defects;
- Finding the major factors exerting influence on the quality of manganese-steel castings;
- Determining quality assessment and control methods in cast products;
- Determining the possible remedies of the manganese steel casting problems and
- Determining the amount of the reduced dimension from the selected components by machining and grinding operations.

1.4 Significance of the Study

This study is devoted to analyze steel casting quality related problems at Akaki Basic Metals Industry. Defect analysis specifically porosity analysis through different experimental procedures and methods are applied to solve the problems. Thus the primary merits of the study goes to the Akaki Basic Metals Industry. Currently there is a steel casting quality problem due to defects which arise from the casting process and there are some ways for reduction of the steel casting defects. The researcher believes that Akaki Basic Metals Industry will be motivated to implement the results of this study on reduction of casting defects and improve its productivity.

The study also merits the academics in Ethiopian casting manufacturing sector. Since there are few and shallow studies in the area, it will give a comprehensive starting point for more specific quality researches for Ethiopian metal processing industries. Government bodies such as Ministry of Trade and Industry, Quality and Standard Authority of Ethiopia and other relevant and interested industries can get important concepts on the overall steel casting quality issues and conditions. The study also highly builds the experience of the researcher to work with others and develop technical and practical skills obtained from the industry. The results from the study can be inferred to other Ethiopian metal processing industries. Finally, anybody who is interested in casting quality especially in steel casting products can get good ideas from the study.

1.5 Scope of the study

The scope of this study is restricted to the main issues of the effects of porosity on the dimension of cast pinion gear, drive disc and head stock components of manganese-steel castings at Akaki Basic Metals industry by determining the root cause of porosity defects based on the data

collected at the site, existing library materials, using the existing laboratory equipment and survey of the industrial work shop and providing the possible remedies for steel casting defects.

1.6 Limitations of the study

It is clear that such a huge research topic requires long period of time to comprehend every detail analysis of the process. Moreover, the availability of materials and resources on the topic is scarce; the laboratory work and software analysis is limited. Casting quality concepts have developed to be multi-disciplinary activities. Doing any kind of study only from the point view of one field of study will result in a limited scope of the very wide knowledge of quality.

CHAPTER TWO: LITRATURE REVIEW

This chapter reviews literatures relevant to the study focusing on the casting process, casting defects and their classification, quality in castings, porosity prediction, porosity reduction and porosity analysis methods.

2.1 Casting process

Casting is one of the direct methods of manufacturing the desired geometry of an engineering component by pouring molten metal into a mold within which the metal subsequently solidifies [7]. The basic principle of casting process is simple: the molten metal is poured into mold or cavity which is similar to required finished shape. But the casting process involves various production steps starting from mold preparation to cleaning and inspection of the final product as shown in Figure 1. A number of materials, pieces of equipment and processes are employed in the production of a cast product. A variety of techniques are used within these two mold casting processes depending on the melting, molding & core-making systems, the casting system and finishing techniques applied [8]. The basic production steps in sand casting are illustrated in Figure 1. Each and every production step has a significant role on the quality of the final product. The occurrence of defects in castings can be attributed to many causes, e.g. the influence of design, process and material parameters or the equipment employed. This complexity makes the defect analysis more of an art-based on experience than an in-depth scientific analysis.

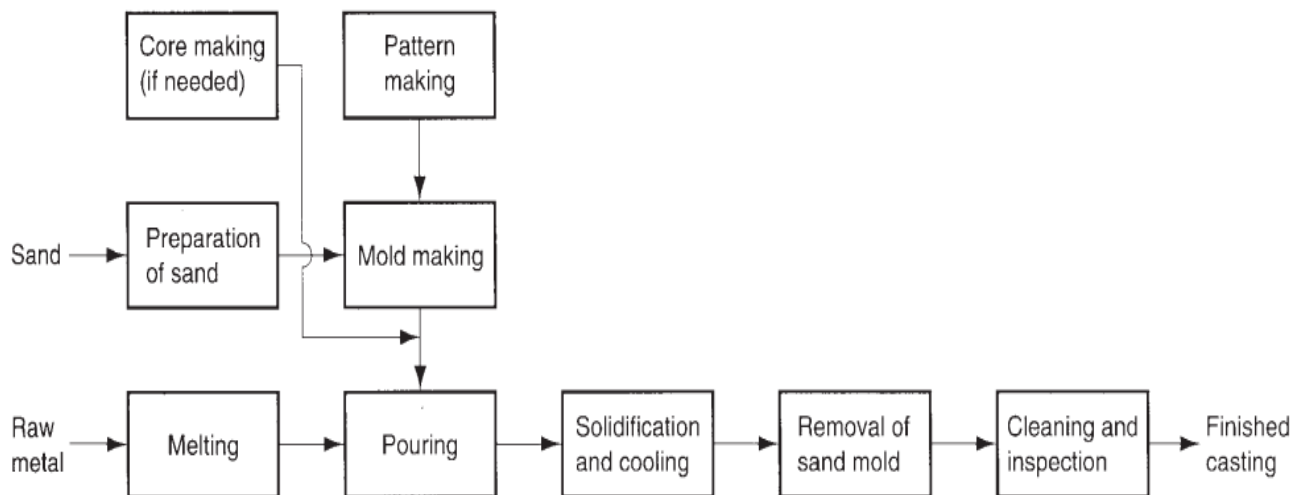


Figure 1: Basic production steps in sand casting process [8]

Foundry production process consists of preparation of molds and molding mixtures, preparation of liquid metal, casting, cleaning of castings, thermal and surface treatment of castings. Many different casting techniques are available. All involve the construction of a container (mold) into which molten metal is poured. The mold contains a cavity whose geometry determines the shape of the cast part. The actual size and shape of the cavity must be slightly oversized to allow for shrinkage that occurs in the metal during solidification and cooling. Different metals undergo different amounts of shrinkage, so the mold cavity must be designed for the particular metal to be cast if dimensional accuracy is critical. Molds are made of a variety of materials, including sand, plaster, ceramic, and metal. To accomplish a casting operation, the metal is first heated to a temperature high enough to completely transform it into a liquid state. It is then poured, or otherwise directed, into the cavity of the mold [4].

As soon as the molten metal is in the mold, it begins to cool. When the temperature drops sufficiently (e.g., to the freezing point for a pure metal), solidification begins. Solidification involves a change of phase of the metal. Time is required to complete the phase change, and considerable heat is given up in the process. It is during this step in the process that the metal assumes the solid shape of the mold cavity and many of the properties and characteristics of the casting are established.

Once the casting has cooled sufficiently, it is removed from the mold. Depending on the casting method and metal used, further processing may be required. This may include trimming the excess metal from the actual cast part, cleaning the surface, inspecting the product, and heat treatment to enhance properties. In addition, machining may be required to achieve closer tolerances on certain part features and to remove the cast surface.

Two basic casting process subgroups are based on expendable and nonexpendable mold casting.

- Expendable mold casting: uses lost molds (e.g. sand molding). Lost molds are separated from the casting and destroyed during the shakeout phase;
- Non-expendable mold casting: uses permanent molds (e.g. die-casting). Permanent molds are reused mold molds.

Inert molds

Very few molds are really inert towards the material being cast into them. However, some molds are very nearly so. This is especially true at lower temperatures. For instance, with the cast iron or steel (permanent) mold used in the gravity die casting or low pressure die casting of aluminum the molds coated with an oxide wash. The metal and mold are practically inert towards each other. Apart from the normal oxidation of the surface of the casting by the air, there are no significant chemical reactions. The usefulness of a relatively inert mold is emphasized by the work of Stolarczyk (1960), who measured approximately 0.5 % porosity in gunmetal casting into steel lined molds, compared with 3.5 % porosity for identical test bars cast in green sand molds. Thus the greater part of the output of the foundry industry consists of castings made in refractory molds chiefly sand castings. Since the properties of the molding material are crucial to the production of sound, dimensionally accurate castings its selection and testing constitutes one of the vital steps in founding. The properties of molding materials can be measured by a wide range of techniques, which provide the basis both for routine foundry control and for the development of new materials.

2.1.1 Molding and core making in sand casting

In sand casting process an expendable mold is used in which the mold is destroyed to remove the casting and a new mold is required for each new casting.

a) Materials for mold preparation

i) Foundry sands

Sand is a material composed of grains of mineral matter ranging from approximately 0.05 to 2mm in diameter. The definition makes no reference to the mineral composition of the grains but common foundry sands are composed of largely silica (SiO_2). High grade specialty sands are available for cores and minerals where special characteristics unique to these minerals are required. The common specialty sands include Zircon (ZrSiO_4), Chromites (FeCr_2O_4), Olivine [$(\text{MgFe})_2\text{SiO}_4$] and Staurolite ($\text{FeAl}_5\text{Si}_2\text{O}_{12}\text{OH}$).

Silica Sands

Foundry sand deposits occur naturally as a result of geologic sedimentary processes of weathering and transportation by wind and water and deposition. The composition of the deposit depend on

the nature of materials that were eroded and in the manner in which they were deposited. During the depositional process, classification by size, composition and specific gravity can take place.

Bank Sands: These are a product of the disintegration of sand stone by the weathering of the wind over vast areas and heaped up in to small banks. Bank sands vary in purity, depending on the foreign materials and minerals with which they are mixed. In many areas they are of high purity and suitable for foundry.

Lake Sands: Are of recent geological origin, composed of sands produced by the erosion of rock in and along the shores of lakes and deposited on the beach.

Preparation of Silica Sands

Many and varied techniques are employed for preparing foundry sands. In the case of bank sand and some lake sands, this may simply involve removing over burden, excavating the sand and loading it in to trucks for shipment to foundry. Most lake and bank sands are dried and screened to remove oversize particles. By additional screening and blending, many different grades of sand are made available to the foundry industry. Where impurities are present, silica sands can be washed, dried, screened and re-blended to make them available in a wide range of fineness and grain distribution.

Specification of sands

Although there is no generally accepted specification for foundry sand, specification should be agreed upon between producer and consumer to meet individual requirements. Most specifications contain tolerances based on a desired sieve analysis and clay content. Tolerances could be established on moisture content, green permeability and green strength in naturally bonded sand. In addition, tolerance may be established on the individual sieves used for running American Foundry Society (AFS) standard sieve analysis.

Comparison of foundry base sands

As per AFS molding and core Aggregate Committee foundry base sands are classified as detailed in Table 1.

Table 1: Comparison of foundry base sands

Characteristics	Silica	Olivine	Chromaites	Zircon
Color	White -light brown	Greenish gray	Black	White – brown
Specific gravity	2.2 – 2.6	3.2 – 3.6	4.3 – 4.5	4.4 – 4.7
Fusion point	(1427 - 1760) ⁰ c	(1538 - 1760) ⁰ c	(1760 - 1982) ⁰ c	(2038 - 2204) ⁰ c
Chemical reaction	Neutral	Basic	Basic	Acidic
AFS grain fineness	25 – 180	40 – 160	50 - 90	95 – 160

General properties of molding sand

For a general view point the molding sand must be readily moldable and produce defect free castings, if it is to qualify as a good one. Certain specific properties have been identified and testing procedures adopted for their quantitative description. The AFS foundry sand hand book sets forth the standard conditions of testing the sand properties. Those properties of most obvious importance include:

1. Green Strength: the green sand after water has been mixed in to it must have adequate strength and plasticity for making and handling of the mold;
2. Dry Strength as casting is poured; sand adjacent to the hot metal quickly loses its water as steam. The dry sand must have strength to resist erosion, and also the metals static pressure of the molten metal;
3. Hot Strength after the moisture has evaporated the sand may be required to possess strength at some elevated temperature. Metal static pressure of the liquid metal bearing against the mold walls may cause mold enlargement, or if the metal is still flowing, erosion, cracks or breakage may occur unless the sand possess adequate hot strength;
4. Permeability: Heat from the casting causes the mold to evolve a great deal of steam and other gases. The mold must have permeable, i.e., pours, to permit the gases to pass off, or the casting will contain gas holes;
5. Thermal Stability: Heat from the casting cause rapid expansion of the sand surface at mold material interface. The mold surface may then crack, buckle or flake off (scab) unless the molding sand is relatively stable dimensionally under rapid heating;

6. Refractoriness: Higher pouring temperatures require greater refractoriness of the sand. The sand, therefore, need to be able to reset such temperature to be usefully utilized as a foundry sand;
7. Flowability: The sand should be easily flowable to make the molding process efficient;
8. Casting finish: It should be able to contribute its share to the good surface of the casting;
9. Collapsibility: Heated sand which becomes hard and rock like is difficult to remove from the casting and may cause contracting metal to tear or crack;
10. Recycling: it should be easily reusable;
11. Conductivity: It should facilitate the process of removing heat from the cooling casting.

Chemical composition

Sands can be grouped in to two types, depending essentially up on their chemical composition.

1. Clay free, known as “silica” or core sand has low clay content (0 - 1.5) % and high silica content (94 - 99)%.
2. Clay bearing, known as “naturally bonded” or molding sand. This sand has medium-high clay content (5 - 20)% and medium-low silica content (80-90)%.

The very high purity sands, 99% SiO₂ are used for glass making. Chemical analysis is rarely carried out by users since they are not primarily interested in composition. Their principal interest associated with this is refractoriness, the ability of the sand to withstand fusion by the temperature of molten metal in the casting operation. Insufficient refractoriness results in “burn-on” the mold or core face softens at the liquid metal temperature and adhesion to the casting surface results. The addition of clay to sand substance will result in corresponding drop in refractoriness.

ii) Binders

Any material which holds sand grains together could be classified as a binder. Binders suitable for foundry use must not only hold sand grains together but also sufficiently resistant to temperature so as not to collapse before the metal has solidified. But after solidification and cooling they must completely collapse to allow the sand to be easily removed from the casting leaving its surface smooth. This ability of the binder to collapse on cooling is known as breakdown and this property is very important in cored castings which are inaccessible to fettling. Binders can be classified in many ways such as by chemical composition, physical form or by hardening process. A simple

classification is by chemical nature and this produces two groups namely inorganic and organic binders.

Inorganic Binders

These are the cheapest binders on the market and some have been used since foundry began. The important binders in this group are clay, a hydrated alumino-silicate used in green sand molding and aqueous sodium silicate used for molds and cores in the CO₂ and several cold setting processes.

Organic Binders

These binders are much more expensive than inorganic binders but this is partly offset by the percentage of addition being much lower less than 2% compared to more than 3% addition for inorganic binders. Unlike the silicate process all organic binders have excellent breakdown properties which make them ideal for the cores of castings where accessibility for fettling is difficult hence the reduced fettling cost makes this binder even more economic.

Oil Based Binders

The oils used in the foundry industry can either be natural oils such as raw lined oils or process oils, synthetic oil and alkyd resin. The raw oils are usually expensive and cheaper oils are usually blended with them to reduce the cost and control properties.

However, of all the family of organic binders, what would be most interesting for the point of view of ABMI foundry would be the resin binders and this shall be dwelt upon accordingly.

Resin Binders

In the last 30 years there has been a tendency to replace oils and silicates with resin for foundry binders. This is because:

- Resin gives in box curing;
- Do not have the breakdown limitations of silicates;
- Requires less skill in the production of molds than when clay bonded hand rammed green sand is used.

Hence, the increased uses of versatile resin binders can therefore be expected to continue although are expensive.

There are many of these materials used in the foundry, from the simple area and phenol formaldehyde resin to the complex furan and polyol resins.

Effects of Resin addition

An increase in resin content will increase the final strength of the sand. Normally, the mixture will have catalyst content as fixed percentage of the resin additions, so that an increase in resin addition will have a proportional increase in catalyst. If the resin is increased with the catalyst addition remaining the same, then the rate of setting will be decreased.

Effect of catalyst addition

The effect on an increase in catalyst on a fixed resin addition is to decrease the setting time and thus decrease the bench life. Figures 2 and 3 show the effect of percent of catalyst addition on compression strength of sand bonded with phenol furan cold set resins of varying nitrogen content and the effect of the percent catalyst on the compression strength after 1 hour of typical furan type cold set resin bonded sand compacts respectively.

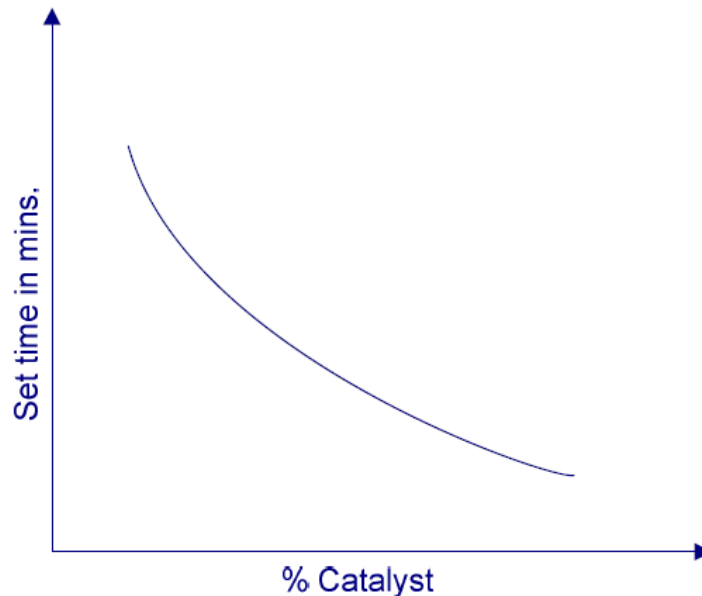


Figure 2: Effect of catalyst addition on the setting time of typical furan type cold set resin bonded sands [10].

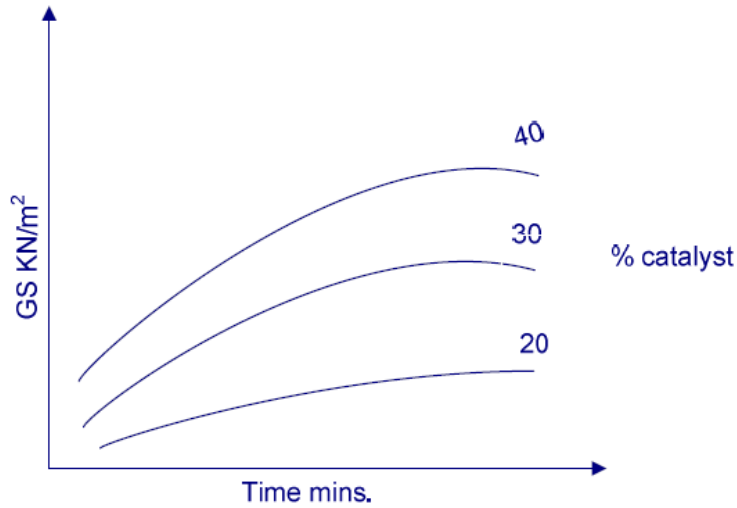


Figure 3: Effect of percentage catalyst on the green compression strength development of typical furan type cold set resin bonded sands [11].

Effect of temperature

Temperature is one of the most important factors in the furan system. A decrease in climatic temperature reduces sand temperature, which reduces the rate of set, increases the bench life and affects mixing by increasing the resin viscosity and hence sand flowability. Figures 4 and 5 show the effect of temperature and furfural alcohol on viscosity of furan resins and setting time respectively.

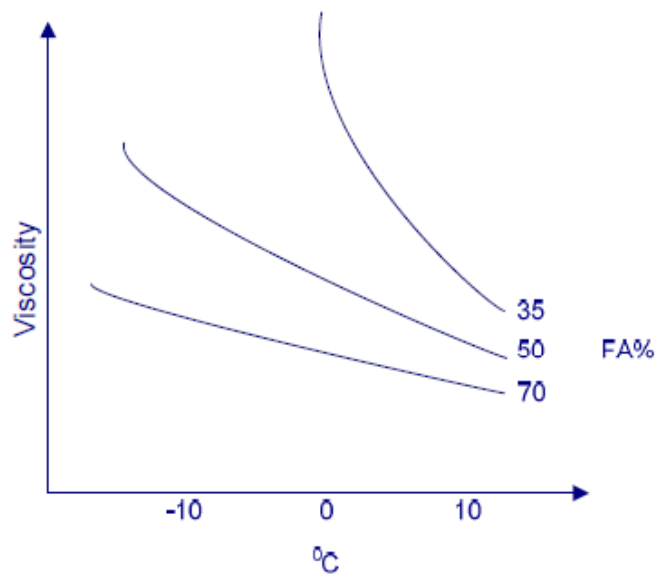


Figure 4: Effect of temperature and furfural alcohol on the viscosity of furan resins [11]

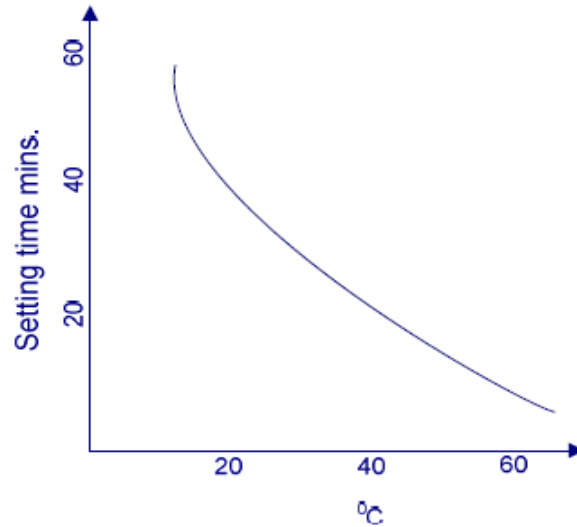


Figure 5: Effect of sand temperature on the setting time of typical furan type cold set [13]

Effect time after mixing

Some systems give very rapid setting times others are slower but it is important to pack the sand in the mold or core box as quickly as possible after mixing otherwise the sand tends to increase in green strength making it more difficult to pack and ram leaving the final cured strength much decreased. It should be remembered that once the resin and acid come together setting begins and it is claimed that the bench life is exceeded once the green strength reach as 10KN/m^2 . Figure 6 shows the effect of time after mixing before compacting on the compression strength after 8hrs of typical furan type cold set resin bonded sand compacts.

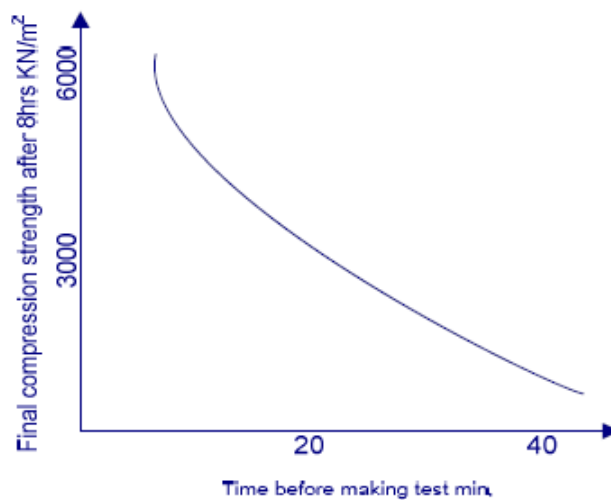


Figure 6: Effect of time after mixing before compacting on the compression strength of typical furan type resin bonded sand compacts [16]

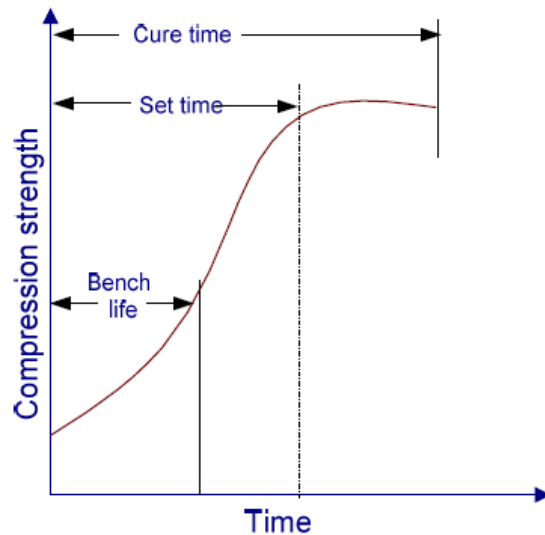


Figure 7: Relationship between bench life, setting time and curing time for typical furan type cold set resin bonded sands [16]

b) Core and pattern making

i) Core making

A core is a performed mass of bonded sand left in the mold cavity to make an internal configuration in the casting. Core print provides a recess in the mold for keeping the core firmly in the mold. Cores can be reinforced with steel wires (for small cores) or with steel rods (for heavier ones). Vent holes are cut for large cores whereas wax threads are introduced for small cores. The major properties of cores to be controlled are: green strength (core strength before backing or hardening), dry strength (core strength after backing or hardening), Permeability (to allow gases to escape), Collapsibility (to remove core and particles from the core during cleaning which is improved by adding wood floor or coal dust.) and the core must not hinder the contraction of the solidified metal in the mold. Careful Consideration of core properties has great contribution for the production of quality castings [10].

ii) Pattern making

A pattern can be defined as a full size model of the casting, used to produce a mold cavity in to which liquid metal is poured. Patterns which are made of wood, metal or plastic, are classified as non-expendable (permanent) patterns. Such patterns are used for producing a number of molds.

Patterns which are made of either wax or polyester are grouped as expendable and they are destroyed during the casting process [11].

Pattern allowance

Pattern allowances are added for the pattern so as to compensate size reduction, size enlargement, pattern withdrawal and other conditions of castings. Usually, there are five types of pattern allowances, namely:

- i. **Shrinkage allowance:** is the amount the pattern must be made larger than the casting to provide for contraction;
- ii. **Draft allowance:** When a pattern is drawn out from the mold, the tendency to tear away the edges of the mold in contact with the pattern is greatly decreased if the surfaces of the pattern are not given a slight taper in a direction parallel to which it is being withdrawn;
- iii. **Machine allowance:** is an allowance given for casting surfaces which require machining. This allowance depends on: the metal employed, shape and size of the part and the casting process;
- iv. **Distortion or camber allowance:** applies only to those castings of irregular shapes such as U-shape or those having large flat areas which are distorted in the process of cooling as a result of metal shrinkage. This allowance depends on the judgment and experience of pattern maker;
- v. **Shaking or rapping allowance:** involves making the pattern size in order to compensate the slight increment of the mold cavity when the pattern is rapped in the mold before it is withdrawn [1].

Careful consideration of pattern allowances in foundry practices has great contribution for quality and economical manufacturing of different castings.

2.1.2 Casting design

Optimum casting design is needed: to achieve internal soundness castings and to evolve a design which will reduce molding, cleaning and machining costs. Minimum section thickness depends on casting process employed and length of the section. The recommended minimum section thickness for sand casting is 4mm [10, 11].

a) Design for molding

Molding design should consider the following points.

- i. Changing design to a single parting line greatly reduces production costs;
- ii. Locate heavier section at or near the parting line where they are easier to feed with risers;
- iii. Undercuts require loose piece;
- iv. Pattern and molding costs can be reduced by eliminating outside bosses;
- v. Efforts to reduce the number of cores greatly minimize molding and production cost.

When the casting is too intricate and its production cost is too high, divide the originally casting in to two or more parts and then cast, and weld by joining. When a casting is to be machined to a close tolerance, it is desirable to do as machining as possible without removing the piece from the machine [13].

b) Riser design

The primary function of a riser is to provide a reservoir of liquid metal during the solidification of a casting to feed and compensate for the shrinkage of the casting. The riser should provide enough quantity of liquid metal for liquid shrinkage and solidification shrinkage. Then a sound casting can be produced without internal shrinkage voids or porosity and external shrinkage defects like sink. It is, therefore essential that the riser should solidify completely only after the casting has solidified. In other words, the solidification time of a riser should be greater than that of the casting.

The secondary functions of a riser are the following:

1. It can act as a vent for gases;
2. It helps to know when the mold is completely filled;
3. It helps to force the metal into mold cavity due to pressure head.

Riser zones and end zones are regions that are free of porosity because a thermal gradient exists in these regions that promotes directional solidification and facilitates feeding flow. By utilizing the riser zone and end zone concepts, it is possible to determine whether or not a casting section fed by a riser will be sound, as well as where porosity will form if the casting section is not sound. This is shown in the following subsections for a top riser feeding a casting section that ends in the mold lateral feeding between top risers and a casting section fed by a side riser.

Riser design parameters

Riser design involves deciding the following parameters [10, 11]:

1. Total volume of the riser;
2. The number of risers and their locations in relation to the casting;
3. The types, shape and size of the risers, and
4. The need and use of chills, padding and riser treatments like exothermic and insulating materials.

Riser volume: The total volume of the risers required would depend on,

1. The shrinkage characteristics of the metal and
2. The shape of the casting.

The solidification shrinkage is quite high for steel (about 4%) and for aluminum (about 6%).

These metals, therefore, require large risers.

Shape of casting: A flat, thin casting cools rapidly and would require a small riser compared to a chunky, cube-like or spherical casting.

Types of risers

There are basically two types of risers: open risers and blind risers. Open risers are exposed to the atmosphere; blind risers are totally enclosed in mold. Blind risers lose heat slowly and are more efficient than open risers, i.e. they can be smaller in size than open risers. Open risers are, however, easy to mold.

Open risers can be top risers or side risers. Top risers have advantage that the pressure due to the height of the metal causes feeding through thin sections and is preferred for light metals such as aluminum. Side risers should be placed at a higher level for proper feeding. Sometimes gating is done through the side riser. The arrangement helps the riser to receive hot metal.

Riser location

Risers are located close to heavy sections to provide the feed metal. For instance, in making a wheel casting, a riser is often required over the hub and one or more risers are placed on the rim.

The number of risers required and their volume can be reduced by using external chills or by using cored holes in heavy sections.

Riser shape

Since our aim is to delay the solidification of a riser, its surface area should be minimized for a given volume, i.e. volume/surface area should be high. The ideal shape of a riser would, of course, be a sphere. But a spherical riser is not easy to mold. The best solution is to design risers with cylindrical and hemispherical section. Open risers are generally of cylindrical shape. Side risers can have a hemispherical bottom.

c) Gating system

Gating system refers to all the passages or channels the metal enters the mold. A gating system may include pouring basin, sprue, runner and gates. The essential features of a typical gating system are illustrated in Figure 8.

The following are the main criterion for a well-designed gating system [10, 11]:

- a. The metal must flow through the gating system with a minimum of turbulence, little aspiration or sucking of gases;
- b. Favorable temperature gradients should be setup to promote directional solidification towards the riser;
- c. The system should be simple, of economical design and easy to mold;
- d. The mold cavity should be completely filled by the molten metal in the shortest possible time;
- e. Slags, dross, inclusions and sand particles should be prevented from entering the mold;
- f. Erosion of the mold should be minimized.

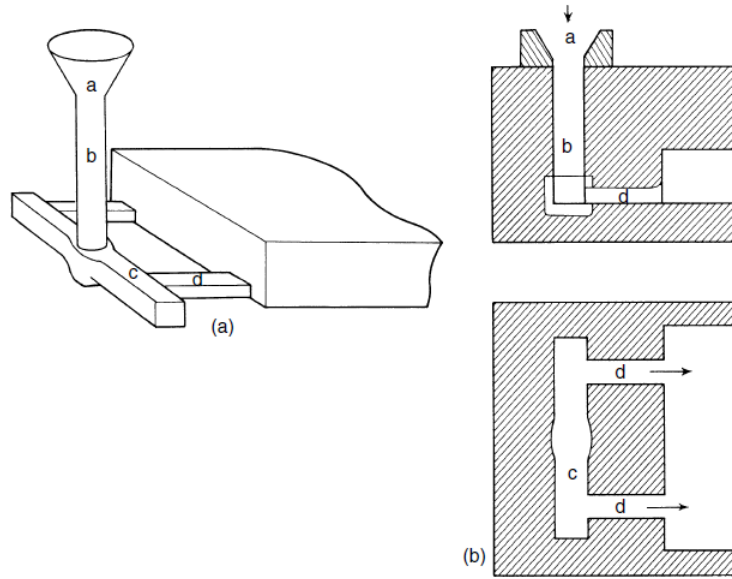


Figure 8: Principal features of a gating system; (a) Bush or basin, (b) sprue or down runner, (c) runner and (d) ingate [15]

Gates can be classified as top, bottom and side or parting line. The principal variations of gating position are illustrated schematically in Figure 9.

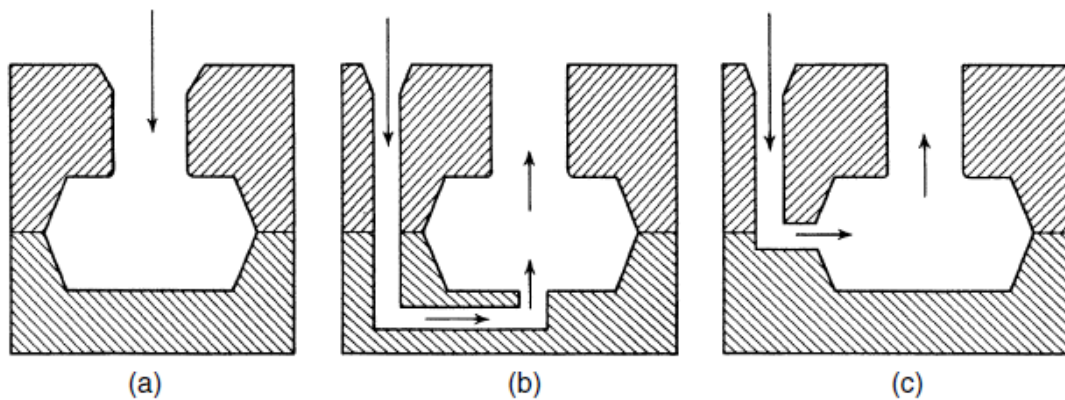


Figure 9: Variations in gating position; (a) Top gating, (b) bottom gating and (c) side gating [15]

Top gating

When metal is poured through a top gate or directly into an open feeder head, the stream impinges against the bottom of the mold cavity until a pool is formed; this is kept in a state of agitation until the mold is filled. The erosive effect of the unconfined stream can be severe, whilst the associated splashing gives opportunity for oxidation. The mold surface can, however, be protected

at the point of impact by preformed refractory tiles; the intensity of erosion can also be reduced, where fluidity of the metal permits, by the use of pencil gates. This method and others which divide the metal stream are unsuitable for alloys which are sluggish or prone to rapid oxidation, but are used with success, for example, in the gating of cast iron. The principal advantages of top gating are its simplicity for molding, its low consumption of additional metal and, above all, the generation of temperature gradients favorable to feeding from top heads; this arises from the proportionately rapid cooling of the first metal poured, followed by the progressive accumulation of metal from above until the mold is full [15].

Bottom gating

Quiet entry of metal into the mold cavity is best achieved by its introduction at the lowest level. Using this method the metal rises steadily through the mold, splashing is eliminated and dislodged molding material tends to be carried to the surface. If bottom gates are used with top feeder heads the resulting temperature gradients are opposed to feeding, but various measures are available to mitigate this effect. Despite the greater complexity of molding the method is much used for heavy castings [15].

Side gating

Molding can be simplified by the discharge of metal into the side of the mold cavity through ingates molded along a parting plane; this practice frequently offers the best compromise between molding convenience and the ideal gating arrangement. Using side gating, progressive mold filling can be achieved by tilting the mold towards the ingates to provide uphill casting conditions [15].

If the gating system, risers and molding are designed properly, the molten metal will be solidified with in a shortest possible time and casting defects will be reduced which lead to high rate of production by reducing manufacturing time as well as labor.

2.1.3 Melting practice

One of the most easily controlled processes although frequently over-looked in importance, is melting. Certain casting problems are directly related to failure in exercising adequate control during the melting process. There are good varieties of furnaces used for melting ferrous and non-

ferrous alloys, each having its own advantages to become more suitable for melting a specific type of alloy. Cupolas, open-hearths, electric arc furnace, electric induction furnace, electric resistance furnaces, fuel fired furnaces, etc. are some of the furnaces employed for melting various materials. The selection of proper types of furnaces depends up on: the melting temperature of the metal, quantity of metal to be melted at a time, fuel cost, installation cost and daily operation and control of composition of the alloy.

Table 2: Relationships between the type of furnace and the alloy type it is most suited for melting

Furnace type	Alloys to be melted
Cupola	Gray cast iron
Low frequency induction furnace	Gray cast iron, ductile iron, bronze casting (specially Al-Bronze casting)
Medium frequency induction furnace	Gray cast iron, ductile iron, steel castings, bronze casting, Al casting
Arc furnace	Steel casting, Gray cast iron
Fuel-fired furnace	Brass and Bronze castings, Al-alloy casting
Rotary furnace	Gray cast iron, ductile iron and steel (to a limited extent)

2.1.4 Pouring

Pouring of molten metal into the mold is one of the critical steps in foundry practice since the behavior of the liquid and its subsequent solidification and cooling determine whether the cast shape will be properly formed, internally sound and free from defects. The great majority of scrap castings acquire that status during the first few seconds of pouring. Few would disagree with that assessment. The success of the pouring operation depends partly upon certain qualities of the metal itself, for example its composition and temperature which influence flow and partly upon properties and design of the mold including the nature of the molding material and the gating technique used to introduce the metal into the mold cavity. Whilst the metal is in the liquid state is also concerned with forces acting upon the mold and with volume contraction occurring during cooling to the solidification temperature.

Attainment of proper metal temperature before pouring is a major aim of good melting practice.

Too high temperature will result in excessive volatilization and oxidation of various elements in the melt. Too low temperature will reduce the fluidity and lead to incomplete filling of the mold, creating defects such as miss-runs and cold shut. Correct pouring temperature depends on the size of the casting and minimum section thickness.

After pouring, the metal is allowed to solidify completely in the mold and cool to a fairly low temperature before the casting is removed (shakeout) from the mold. It is important that the shakeout temperature is monitored so that the castings are not removed too early from the molds. If the casting is allowed to cool in air, instead of in the sand mold itself, it will not cool at a faster rate and may attain higher hardness or form hard spots. It may also develop cracks [15, 32]. Considering optimum pouring temperature, preheating ladles before collecting the melt and keeping proper solidification time for the mold not only saves time, labor, and resources but reduces casting defects.

2.1.5 Solidification

Solidification phenomena are the heart of most of the product manufacturing processes. From conventional manufacturing processes like foundry casting, arc welding, ingot casting etc. to the latest technologies like crystal growth, near-net shape processing, laser processing, plasma processing and solidification phenomena play a dominant role in process as well as product optimization. Over the last couple of decades, there has been significant progress in the fundamental understanding as well as in the modeling approaches to solidification phenomena. This has led to better product quality and higher productivity of conventional processing. Besides these, the new advances in the understanding of the process have led to the development of several new technologies [16].

The pouring of metal into a relatively cool mold initiates the processes of solidification, during which stage the cast form develops cohesion and acquires lasting structural characteristics. The mode of freezing exercises a twofold influence upon the final properties of a casting. The normal metallographic structure determines many of the properties inherently available from the cast metal. This structure the grain size, shape and orientation and the distribution of alloying elements as well as the underlying crystal structure and its imperfections is largely determined during crystallization from the melt. Even in those cases where the cast structure is modified by

subsequent treatments it still exerts a residual influence upon the final structure. The properties and service performance of an individual casting are however, also a function of its soundness the degree of true metallic continuity. The volume shrinkage accompanying the change of state must be fully compensated by liquid feed if internal voids are to be prevented.

Structure and soundness being dependent upon the mechanism of solidification are influenced by many factors including the constitution and physical properties of the alloy. Steels, bronzes and cast irons for example exhibit wholly different feeding characteristics. Other important factors are the pouring and mold conditions and it is with the manipulation of these conditions to achieve full control of the pattern of freezing that much of the technique of founding is concerned. In these section the fundamental mechanisms of solidification of steel casting in particular emphasis on composition of defective components on my study will examined, many of the casting defect appear in the casting is related to solidification of the metal structure. At these stage the molten metal is affected by many of the foreign material either gases or solid mold material reaction. In order to produce parts with casting free from defect the solidification pattern the casting practice, the pouring principles are the most decisive factors that due consideration.

The solidification of most alloys is accompanied by appreciable volume contraction. The magnitude of this contraction varies depending up on the metal type the precise influence of this contraction upon the casting varies with freezing conditions. When the solidification process is characterized by sharp demarcation between solid and still liquid zones, as occurs in pure metals and alloys of narrow freezing range the contraction is readily compensated by a fall in the free liquid surface in the system. Provided that enough liquid is present this process can continue until the casting itself is wholly solid the supply of liquid being maintained by external feeder heads or risers. The purpose of a feeder head therefore, is to provide reservoir of liquid metal under a pressure head sufficient to maintain flow into the casting. Without feeding the final casting will be subject to shrinkage defects in the form of major internal cavities, center line or filamentary voids, or surface sinks and punctures. These forms of defect examined in more in detail the alloy constitution and thermal conditions are such that there is no clearly defined macroscopic interface between solid and still liquid regions.

Solidification progresses simultaneously throughout a zone which may in certain cases comprise the entire casting this zone contains crystals at various stages of growth intimately mixed with residual liquid of lower melting point and the metal is said to be in a pasty or mushy state. The sites of contraction are now dispersed through an extensive region within the casting, so that the mechanism of feeding is more complex: Three successive stages are encountered. At an early stage, whilst bodies of growing crystals are suspended out of mutual contact in the liquid free movement of the whole can take place as before to provide feeding through a fall in the level of the free surface this is termed the mass feeding stage and a feeder head provides compensating metal under the necessary pressure. At a certain stage however, the grains form a contiguous network of solid. Movement of liquid is then confined to the diminishing inter-granular arrangement.

Table 3: Flask opening time after pouring (for steel)

Weight (tons)	0-0.1	0.1-0.2	0.2-0.4	0.4-0.8	0.8-1.2	1.2-2	2-5	5-10	10-15	15-25	25-50	50-75
Mold opening time (hr)	0.5-2	2-4	3-6	4-8	8-10	10-12	16-25	30-35	40-45	72-90	90-120	180-200

Crystallization from the melt

Matter in the crystalline state exhibits long range order being characterized by regularity of atomic spacing over considerable distances. Metallic crystals deposited from the melt although possessing internal symmetry are commonly of irregular external form as a result of uneven growth rates and mutual constraint in the last stages of freezing. The allotriomorphic grains thus the normal crystalline unit in the cast structure although in the case of the eutectic grain or cell two or more separate crystal structures are Associated through the simultaneous growth of separate phases. Since the crystal lattice usually represents a more closely packed state of matter than the liquid, freezing is almost invariably associated with volume contraction. The reduction in molecular motion is also accompanied by liberation of energy in the form of latent heat of crystallization which exerts a marked effect upon the rate and mode of crystal growth. Crystallization from a metal melt involves the successive stages of nucleation and growth. The location and relative rates of these two phenomena within the liquid determine the final structure

of the solid and establish the extent to which freezing is directional or occurs in a discrete manner throughout the liquid.

Fluidity of liquid metals

Although other terms such as castability have been used to describe certain aspects of flow behavior the term fluidity is most widely recognized. In the broad sense it can be defined as that quality of the liquid metal which enables it to flow through mold passages and to fill all the interstices of the mold providing sharp outlines and faithful reproduction of design details. It follows that inadequate fluidity may be a factor in short run castings or in poor definition of surface features. It can at once be appreciated that fluidity is not a single physical property in the same sense as density or viscosity but a complex characteristic related to behavior under specific conditions within a foundry mold. In considering the factors influencing flow viscosity might be expected to predominate. Viscosity is defined as the force required moving a surface of unit area at unit velocity past an equivalent parallel surface at unit distance it is thus a measure of the capacity of a liquid to transmit a dynamic stress in shear. When liquid is flowing in an enclosed passage, its viscosity will determine the extent to which the drag imposed by the passage wall is transmitted to the bulk of the liquid it will therefore influence the rate of flow, which is found to bear a simple reciprocal relation to the viscosity. More directly related to the capacity of a liquid to flow under its own pressure head is the kinematics viscosity, that is the absolute viscosity divided by the density. Further consideration indicates that these properties will not be decisive in determining the relative mold filling capacities of metals under foundry conditions. One of the fundamental characteristics of the liquid state is the ability of any liquid, however viscous, to conform in time to the shape of its container. This would occur rapidly in the case of liquid metal held at constant temperature since viscosities of liquid metals are very low under casting conditions failure to fill the mold cavity results not from high viscosity but from premature solidification. Thermal conditions and mode of solidification are thus the critical factors with respect to cessation of flow. The concept of fluidity takes these aspects into account.

The molten metal passes through the following four stages till the solidification takes place into the mold: liquid stage; mushy stage; plastic stage and solid stage.

2.1.6 Cleaning and inspection of castings

Cleaning (fettling)

This may involve removal of cores, removal of adhering sand, metal nails and chills, cutting of gates and risers and grinding operations. Cleaning cost may form a considerable part of the overall production cost; therefore, every effort should be made to reduce it. After cleaning, particularly after grinding, certain defects such as blow holes or cracks in the castings may be repaired by welding.

Inspection

In foundry, there are two stages in inspection: process inspection and product inspection. Process inspection refers to the inspection procedures connected with various stages or process of manufacture. Patterns, molding equipment, molding and core sands are periodically tested. Cores are inspected for strength, collapsibility, dimensions and evolution of gases. The composition of metallic raw materials and the melt are checked in the chemical metallurgical laboratory. Product inspection can be performed by destructive or non-destructive methods.

Destructive tests (DS) include tensile, transverse, impact, hardness and bending. Nondestructive tests (NDT) which are widely used in castings including visual examination, sand, percussion and impact, ultrasonic, pressure testing, dye penetrant, electric conduction, magnetic particle and radiography (x-ray and gamma ray).

The price of a product can be reduced by considering manufacturing cost which includes reduction of fettling and/or cleaning operation so that the inspection will show positive result. Due to this, the castings are highly demanded by the internal and external customers of the organization.

2.2 Casting Defects

Foundry industries in developing countries suffer from poor quality and productivity due to involvement of number of process parameters in casting process. Even in a completely controlled process, defects in casting are observed and hence casting process is also known as process of uncertainty which challenges explanation about the cause of casting defects [17].

Under practical circumstances castings, like all metallurgical products, contain voids, inclusions and other imperfections which contribute to normal quality impairment. Such imperfections begin to be regarded as true defects only when the satisfactory function or appearance of the product is in question. In such cases, the possibility of salvage, if worse, rejection and replacement should be considered. The decision should be based upon not only the defect itself but also upon the significance in relation to the service function of the casting and the quality and inspection standards being applied [18, 19].

2.2.1 Classification of casting defects

A defect may arise from a single clearly defined cause which enables the remedy to be more specific and straightforward. It may, however, result from a combination of factors, so that the necessary preventive measures are more obscure. All foundry men are familiar with the persistent defect which defies explanation and finally disappears without clarification of its original cause.

Close control and standardization of all aspects of production technique offers the best protection against such troubles. More specific precautions can be taken in those cases where there is a known susceptibility to a particular defect, whilst the radical approach of design modification may need to be considered in the extreme cases which do not respond to changes in foundry technique. Defects can, above all, be minimized by a clear understanding of their fundamental causes [15]. The general origins of defects lie in three sectors [19]:

1. The casting design;
2. The technique of manufacture - the method;
3. The application of the technique - 'workmanship'.

The AFS classified the defects occurring in castings in the following types resulting from causes attributable to 10 processes. The defects and their general causes are provided in table 3.

The logical classification of casting defects presents great difficulties because of the wide range of contributing causes, but a rough classification may be made by grouping the defects under certain broad types of origin [15]. This arrangement has been adopted for this study and seven categories of defect are considered, as follows:

1. Shaping faults arising in pouring;
2. Inclusions and sand defects;

3. Gas defects;
4. Shrinkage defects due to volume contraction in the liquid state and during solidification;
5. Contraction defects occurring mainly or wholly after solidification;
6. Dimensional errors;
7. Compositional errors and segregation.

Although these groups are not mutually exclusive, they afford reasonably clear lines of division in most cases. It should be noted that the defects which will be considered in this study are mainly those of particular character to Manganese Steel castings.

Table 4: Casting defects

No.	Name of casting defect	No.	Name of casting defect
1	Blow holes	15	Rat tail
2	Buckle	16	Rough casting surfaces
3	Burn on sand	17	Sags
4	Casting overweight	18	Scab
5	Cold shuts	19	Sand inclusion
6	Cuts washes	20	Seams
7	Cracks	21	Slag spots
8	Dirt spots	22	Swells
9	Drops	23	Thick thin section
10	Fin	24	Veining
11	Hot tears surface cracks	25	Shrinkage cavity
12	Misrun	26	Short pours, run-out
13	Penetration	27	Coarse crystalline structure
14	Pin hole		

The possible causes for the defects given in table 4 are shown in table 5.

Table 5: Possible causes for casting defects

Possible causes	
a	Improper hydraulic pressure
b	Improper test specimen
c	Improper design
d	Improper quality design
e	Improper raw material and improper product handling
f	Improper chemical composition, Improper gas composition
g	Improper machining
h	Improper heat treatment

Blow hole, sand inclusion, sand burning, cracks, hot tears, surface cracks, pin holes and shrinkage cavity are the major defects appear in different components of the products of the foundry work shop of Akaki Basic Metals Industry.

During the process of casting, there is always a chance where defect will occur. Minor defect can be adjusted easily but high rejected rates could lead to significant change at high cost. Therefore it is essential for to have knowledge on the type of defect and be able to identify the exact root causes, and their remedies.

Casting defects in four main groups as [17];

1. Filling related defects: blowhole, sand burning, sand inclusion, cold lap or cold shut, misrun, gas porosity;
2. Shape related defects: Mismatch defect, distortion or warp, flash defect;
3. Thermal defects: cracks or tears, shrinkage, sink marks;
4. Defects by appearance: metallic projection, cavities, discontinuities, incomplete casting, incorrect dimension or shape, defective surfaces, rat tail and buckles.

Since sand castings are used to manufacture complex shapes, the castings are likely to have one or more defect. The presence of defects leads to casting rejections. The metal casting process suffers from the following types of defect [20]:

- Improper closure: flash, mismatch;

- Incomplete filling: cold shut, misrun;
- Gaseous entrapments: blow holes, gas porosity;
- Solid inclusions: sand inclusions, slag inclusions;
- Solidification shrinkage: cavity, porosity, centerline, sink;
- Hindered cooling contraction: hot tear, crack, distortion.

The improper tool design causes unacceptably high turbulence, unfilled thin sections, solidification before complete filling and hindered heat flow. These cause the major three defects viz. incomplete filling, solidification shrinkage and hindered cooling contraction.

2.2.2 Defect analysis in steel casting

Since the manufacturing process of steel castings is complicated and the production system consists of cooling high-temperature molten metal down to normal temperature within a specific period of time, one must admit that as things now stand it is impossible to completely eliminate the occurrence of all kinds of defects.

The training manual organized by JIACIN JAPAN for cast steel manufacturing technique [21], clearly explains that steel castings are important component part of important machinery and equipment, and depending on the application they involve complex requirements referring to dimensions, shape, material, strength, tenacity, heat resistance, acid resistance, abrasion resistance and other relevant aspects. Such being the case, they must be submitted to strict non-destructive tests with the object of confirming that they are in conformity with the quality requirements set forth in the quality specifications of steel castings.

The occurrence of products with bad quality means not only additional mending cost for restoring defective items to the required quality level, but also delay in the term of delivery, loss of confidence and other problems. Moreover, when problems related to the quality of steel castings occur frequently, the reliability of this category of products as a whole may be lost, resulting into the switching of the users to other kinds of products such as steel forgings, steel plates or their combination, and that would mean a reduction in the demand of steel castings. Thus, manufacturing steel castings of superior quality and meeting the terms of delivery required by the clients is a fact of fundamental importance for the very survival of the steel foundries. Defining

the borderline of the acceptable or rejectable quality of product is quite difficult. It is deemed as particularly important to clearly define the quality standards, to include the test/inspection items and the respective judgment criteria in the specifications, to decide the issuance/acceptance of the orders in conformity with these criteria and standards, to manufacture the products within the standard system about mutual satisfaction both to manufacturer and user, to confirm the quality, and to deliver the product on time.

2.3 Porosity defects in metal castings

Porosity is one of the regular problems which impact the quality of the castings and worsen the mechanical properties of a product. Porosity is the most persistent and common complaint of casting users. Forgings, machined parts and fabrications are able to avoid porosity with ingot cast feedstock, mechanical processing and automated inspection of sample shapes. Controlling porosity depends on understanding its sources and causes. Significant improvements in product quality, component performance, and design reliability can be achieved if porosity in castings can be controlled or eliminated [22]. Porosity in castings is due to bubbles or gases being trapped during solidification.

Porosity sources include entrapped air during filling, centerline shrinkage that occurs during the final solidification, blowholes from unvented cores, reactions at the mold wall, dissolved gases from melting and dross or slag containing gas porosity. In addition, due to a decrease in the solubility of gases during solidification, gases dissolved in a molten alloy are rejected from the solid to the liquid, resulting in an increase in the gas concentration in the remaining liquid. As a result, the last liquid to solidify can have relatively high dissolved gas content and exceed the limit of solubility. Dissolved gases in the molten irons may come from various sources, but charge materials containing high amounts of nitrogen, oxygen, hydrogen and decomposing organic mold binders during pouring are the most common sources [23]. Volume contraction during solidification creates shrinkage in castings. Some of the factors contributing to shrinkage are the density differences of liquid and solid, the viscosity of the liquid, the solidification range, the solidification rate, and the permeability of the mushy zone [24].

Porosity in castings can be grouped into one of two broad categories (macro-porosity or micro-porosity) on the basis of scale and mechanism of formation. Macro-porosity is generally large in

scale and forms as a result of solidification of liquid that has been enclosed by a solidified material. The size of the resulting pore or cavity is dependent upon the volume of enclosed liquid and the volume shrinkage associated with the liquid to solid phase transformation. Macro-porosity is easily corrected by proper gates and risers within the mold and/or using chills and and/or exothermic to control the progress of solidification [20].

In contrast, micro-porosity forms interdendritically at the scale of the microstructure. Thus, its formation is more complex mechanically, more difficult to predict, and generally more difficult to correct. There are two primary sources of micro-porosity: solute gas precipitation in the interdendritic liquid, and/or poor liquid feeding from volume shrinkage within the mushy zone.

2.3.1 Classification of porosity defects

Porosity related defects in shape casting are major cause of casting rejections and rework in the casting industry. Porosity in castings can be classified by the size of the pores as [25]:

- i. Macro-porosity and
- ii. Micro-porosity.

And by the cause for the pores forming:

- i. Shrinkage porosity and
- ii. Gas porosity.

Porosity is usually to be either hydrogen porosity or shrinkage porosity. Hydrogen porosity is the term given to porosity that is generally rounded, isolated, and well distributed. Porosity that is interconnected or clustered and an irregular shape corresponding to the shape of the interdendritic regions are usually termed shrinkage. In general, the occurrence of micro-porosity in alloys is due to the combined effects of solidification shrinkage and gas precipitation [26].

Defects that arise from shrinkage solidification are classified as:

- External defects: pipe shrinkage and caved surfaces;
- Internal defects: macro-porosity and micro-porosity.

Generally short freezing alloys are more prone to internal defects, whereas long freezing alloys are more prone to surface depressions [27].

2.3.2 Formation of shrinkage porosity

From a scientific point of view, the problem of porosity formation is complex and most interesting. The thermal properties of the alloy being cast (latent heat of fusion and thermal conductivity), the composition of the alloy (freezing range and dissolved gas content), the mold properties, and the geometry of the casting are all important to the properties of the final cast product. However, the relative effect of these variables is very complicated. The problem has been studied in detail for nearly 20 years, but there appears to be no clear agreement as to which mechanisms control the formation of porosity. In the absence of a clear scientific understanding, foundry men used empirical rules to design their molds.

Shrinkage is the term for obstruction of fluid flow coupled with a difference in the specific volumes of liquid and solid metal. As the casting solidifies, metal that is still fluid will try to flow to compensate for the liquid/solid volume change; however, the flow may be hindered by the solid which has already formed. If a poorly fed region is large and completely cut off from a source of liquid metal, then a large void (generally greater than 5 mm in maximum length) is formed. The resulting void is termed 'macro-porosity'. (Note that gas solubility differences may contribute to macro pore formation as well). The area in which macro pores form solidifies after the surrounding region, termed as a 'hot spot' with reference to the islands of hot metal completely surrounded by colder material [20].

Gas porosity

The gas can be from trapped air, hydrogen dissolved in alloys, moisture from water based die lubricants or steam from cracked cooling lines.

Air is present in the cavity before the shot. It can easily be trapped as the metal starts to fill the cavity. The air is then compressed as more and more metal streams into the cavity and the pressure rises. When the cavity is full it becomes dispersed as small spheres of high pressure air. The swirling flow can cause them to become elongated.

Gas porosity can be sub-divided into a further three causes [28]:

- Firstly, gas held in solution in the molten metal can be precipitated as the metal solidifies, simply as a result of the reduced solubility on freezing;

- Secondly, if the mold is filled under very poor conditions, air can be entrained in the metal stream and then trapped as the metal solidifies;
- Finally, the sand binders used to make the molds and cores often break down when in contact with the molten metal and the gaseous decomposition products can force their way into the solidifying metal, leading to defects which are normally known as 'blows'.

These different types of gas porosity defect vary in their size, distribution, distance below the casting surface and morphology. It follows therefore that the cause of such defects in a real casting can be deduced from a careful examination.

Most of the problems experienced in producing sound metal casting arise because of lack of control of dissolved gas or reaction gas in the casting during the period of solidification. Gases are absorbed in molten metals from different source listed below.

Furnace charge

- Wet furnace charge (effect of previous melting cycle);
- Electrolytic source alloying additions containing hydrogen resulting from the reducing conditions employed in melting;
- Lubricants on the scrap metal;
- Fluxes slag making additions.

Furnace refractory

- Refractoriness of furnace spouts, foundries and ladles if not properly preheated before they came in contact with molten metal they may help gas absorption through dissociation of steam at the contact surface.

Furnace atmosphere

- Furnace atmosphere may contain water vapor, CO, CO₂ and SO₂ as products of fuel combustion and the normal atmospheric gases such as nitrogen and oxygen;
 - Gas absorption from furnace atmosphere may be enhanced by conditions peculiar to a melting furnace e.g. dissociation of gas molecules in electric arc melting. Atomic gases (say atomic nitrogen) thus resulted have increased solubility in molten metal.
- a) Molten metal absorb gases while passing through air during tapping from the furnace in to the ladles or when being transported from ladle to mold.

- b) Molten metal may also absorb gases from within the mold if the mold material contains excess moisture or volatile hydrocarbons.

There are three major sources that may contribute to porosity formation in iron castings. These are [29]:

1. High initial gas content of the melt, originated from either the charge ingredients, melting practice or atmospheric humidity;
2. Reaction of carbon and dissolved oxygen under certain melt condition;
3. Mold-metal reactions between evolved mold and core gases at the solidifying casting surface.

In addition, any combination of these three sources may have a cumulative effect on promoting porosity formation. However, the gases normally held responsible for surface porosity defects are nitrogen and hydrogen.

The appearance of the subsurface porosity defects resulting from the preceding sources may take numerous shapes but usually form as either small, spherical holes (sometimes elongated or pear-shaped), called pinholes, or larger, irregularly rounded holes or irregularly shaped fissure type defects.

Gas is absorbed both in molten metal and in solid metal but as a general rule the amount of gas absorbed in molten surpasses by far the amount of residual gas that may reasonably be present in the solid metal. Such being the case, bubbles that are the most serious problem out of the defects occurring in castings are generated on the occasion of the solidification of the metal. The types of absorbed gas that becomes causes of formation of bubbles are mostly hydrogen, oxygen and nitrogen [9].

Closely related to air bubbles trapped during filling are gas bubbles that are blown into the liquid from a core or mold much like a kid blowing bubbles using a straw. All porosity is the result of bubble formation and all bubbles follow a basic relationship.

Pressure of gas-forming bubble > Pressure inside the liquid + 2 * surface tension / radius of bubble

$$P_b > P_{Hd} + 2\sigma / r \quad (1)$$

Porosity in castings contributes directly to customer concerns about reliability and quality. Controlling porosity depends on understanding its sources and causes. Significant improvements in product quality component performance and design reliability can be achieved if porosity in castings can be controlled or eliminated. Porosity in castings is due to bubbles being trapped during solidification. Porosity sources include entrapped air during filling, centerline shrinkage that occurs during the final solidification, blowholes from unvented cores, reactions at the mold wall, dissolved gases from melting and dross or slag containing gas porosity.

2.3.3 Porosity sources

One source of porosity in castings is a failure to eliminate all the air in the mold cavity. Most often this porosity appears to be a misrun or incomplete casting. In skin forming alloys when the filling event is chaotic air bubbles can be entrapped in the casting sometimes the air bubbles deflate leaving the oxidized skin. As a simple example illustrating the basic relationships of size, pressure and temperature entrapped air bubbles are a good starting place. Suppose an air bubble is trapped in a casting during pouring and is unable to escape before solidification [30].

If the air bubble is originally 10 mm in diameter (a little larger than 3/8in. and a volume of about 0.5 ml), the higher temperature of the molten metal will cause the air bubble to expand initially and then contract until the metal freezes. The size change due to temperature at solidification can be calculated using Charles' Law by multiplying the original volume of the bubble by the ratio of the final temperature divided by the initial temperature.

Final volume = initial volume x (final temperature / initial temperature)

$$V_f = V_i \times \left(\frac{T_f}{T_i}\right) \quad (2)$$

- a) Charles' Law Temperature must be in absolute terms. For example room temperature is usually given as 298°K (25°C or 77°F). For steel, the final temperature of 1773°K (1500°C or 2732°F) gives a volume of 3 ml (18 mm in diameter or almost 3/4 in.).

The size of the final bubble must not only be adjusted for temperature change but also for pressure. Just like the pressure increases as you go deeper in water, the liquid metal pressure (metallostatic head) increases as you go lower in the casting.

The pressure can be calculated from the density of the metal and the depth from the top of the sprue. For example, at 200mm down in the casting (about 8 in.) the pressure in steel is the density (7850 kg/m³) times the depth (0.2 m) or 1570 kg/m² (0.15 atm. gage or 1.15 atm. absolute). Using Boyle's Law the size change due to pressure can be calculated by multiplying the initial volume of the bubble by the ratio of the initial pressure divided by the final pressure.

Final volume = initial volume x (initial pressure/ final pressure)

$$V_f = V_i \times \left(\frac{P_i}{P_f}\right) \quad (3)$$

b) Boyle's Law

Normal atmospheric pressure is one atmosphere. For steel, this pressure due to the metalostatic head reduces the larger volume of 3 ml due to temperature to 2.7 ml (17 mm in diameter or about 5/8 in).

Member companies of the Japan Castings Society Foundation [21] carried out a survey on the causes exerting influence on the gas defect and high temperature crack, out of the casting defects. Results of the survey are summarized as follows.

2.3.4 Causes of blow holes and pin holes

Hydrogen, nitrogen and oxygen are gas components which work as causes of blow holes and pin holes.

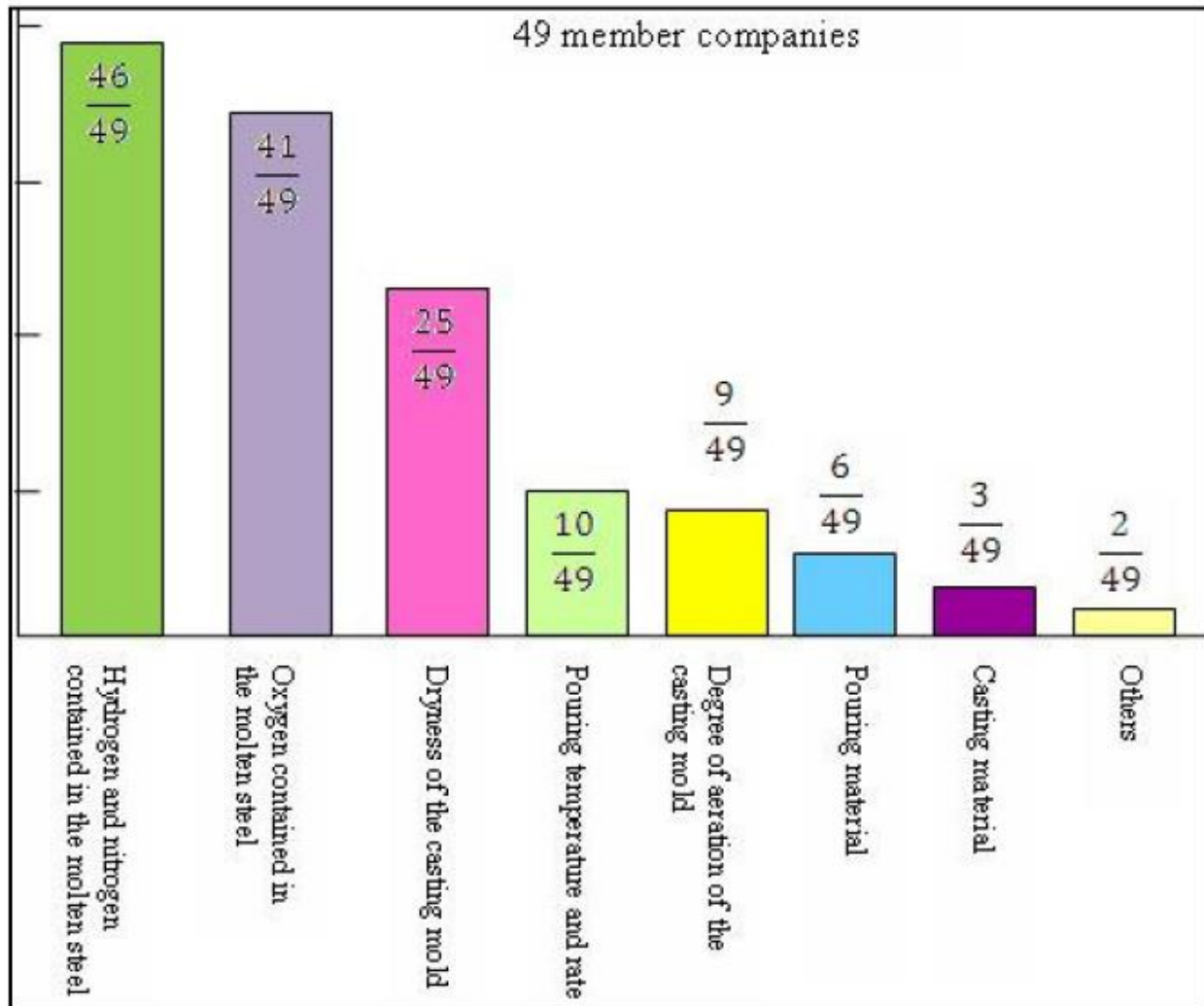


Figure 10: Causes of blow holes and pin holes [21]

Hydrogen and nitrogen contained in the molten steel lead the list of the causes of blow holes and pin holes occurring in steel castings, and they are followed by oxygen contained in the molten steel.

2.4 Summary of casting defects

During the process of casting, there is always a chance for occurrence of a defect. Minor defect can be adjusted easily but high rejected rates could lead to significant change at high cost. Table 5 shows various casting defects and causes.

Table 6: Various casting defects and their causes [4, 12, 13, 17, 28]

No	Defect	Description	Cause
1	Blow holes	Blow is relatively large cavity produced by gases which displace molten metal from convex surface. Blow holes are large spherical shaped gas bubbles.	Lower permeability, excess organic in the molding or core sand, excess dissolved gases in the molten metal, inadequate venting of the core, wet, greasy or rusty chaplets and chills and inadequate venting of the mold.
2	Shrinkage	An essentially solidification contraction.	Improper location of gate and risers, inadequate runners, gates and risers, poor design of the casting, improper filleting of corners, improper pouring temperature, and failure of directional solidification,
3	Hot tears and hot cracks	A crack often scarcely visible because the casting in general has not separated into fragments. The fracture surfaces may be discolored because of oxidation.	Poor design of the casting, improper and inadequate placement of chills & risers, improper pouring temperature of the metal, poor collapsibility of core and mold materials.
4	Cold cracks	Sudden chilling of the casting.	Sudden removal of the casting from the mold, spraying of water over hot casting, and severe handling of the casting before complete stress relieving.
5	Misrun & cold shut	When the metal is unable to fill the mold cavity completely and thus leaving unfilled portion called misrun. A cold	Low metal fluidity due to low pouring temperature and improper alloy analysis, small gate and low pouring rate, thin casting sections,

		shut is called when two metal streams do not fuse together properly.	small sprue height and improperly positioned gates and risers.
6	Run out and bust out	Unintentional escape of molten metal from a mold.	Too large pattern for a flask, pattern placed much too close to the flask, misalignment of cope and drag, excessive pouring pressure, improper seating of mold joints.
7	Pour short	The upper portion of the casting is missing. The edges adjacent to the missing section are slightly rounded; all other contours conform to the pattern. The sprue, risers and lateral vents are filled only to the same height above the parting line.	Insufficient metal in the ladle, interruption during operation.
8	Inclusions	Non-metallic particles in the metal matrix.	Breaking of core, gating, etc. at the time of metal pouring due to: poor ramming of molding sand, interior core and mold sand, rough handling of the molds and poor gating.
9	Porosity	Indicates a large number of uniformly distributed tiny holes. Pin holes are tiny blow holes appearing just below the casting surface.	Absorption of hydrogen by the metal, higher temperature of the mold & slower rate of solidification
10	Metal penetration	Flowing of the molten metal between the sand particles in the mold.	Coarse molding and coarse sand, soft ramming of the mold sand, and high metal fluidity due to excessive metal temperature.

11	Swell	Deformation of vertical mold surface due to hydrostatic pressure caused by moisture in the sand.	Soft ramming of the mold, low strength of the mold, if the metal is poured too hard or too rapidly and if the sprue is too high.
12	Shift	Misalignment of two parts of the mold or incorrect core location.	For core shift: if the core seats are undersized or oversized, if incorrect size chaplet is used and if there is misalignment of cores in assembling cored molds. For mold shifts: if the mold boxes are worn out and if cope and drag are misaligned.
13	Fins	Flat projection of irregular thickness, often with lacy edges, perpendicular to one of the faces of the casting. It occurs along the joint or parting line of the mold, at a core print, or wherever two elements of the mold intersect.	High metal pressure and hard pouring, if flasks have insufficient weight at the time of pouring, if mold and core sections fit poorly and run out.
14	Crushes	Buckling or breaking of a section of a casting mold & an indentation in the surface of a casting.	During core setting or assembling the mold and fitting core in undersized core prints.
15	Hard spots	A small round mark, differing in color or texture from the casting.	Faulty metal composition and casting design.
16	Shot metal	Small, spherical particles of metal adhered on the casting.	Faulty gating system, low temperature of the metal, high sulphur content of the metal and higher moisture content in the

			molding sand.
17	Fusion	Fusing of the mold sand leading to sand burning and sintering to the casting.	The refractoriness of the facing and core sand being low, excessive metal pouring temperature, and faulty gating system.
18	Drop	An irregularly-shaped projection on the cope surface caused by dropping of sand.	Low green strength of sand, too soft ramming of the sand and insufficient reinforcement of any sand projections.
19	Warp	Distortion due to warp age.	Lack of directional solidification, and casting having very large and wide flat surface as a result of poor design

2.5 Quality in casting

Quality can be perceived in accordance with requirements, customer needs. It, in return, implicates necessity of verification of this accordance, i.e. quality inspection. That means how, on the ground of this inspection, to improve quality of articles and services. To speak about possible usage of repairing methods in firm, it is necessary to mention exact qualifications of criteria usage of quality improvement tools. Separation of quality criteria takes place to investigate all spheres of formation and usage of products: preproduction, production and after production phase. Each of these phases is characterized by occurrence a sequence of information about quality, quality features evidenced in certain forms. Result assembled criteria of production can be used for effective application of different kinds of analytic tools [31].

Suitable manners permit an analysis in every phase of product formation from designing to final product and its exploitation because quality question is central question in every production stage. The approach to casting quality has undergone a long period of change, involving a broadening of the subject to enhance many more aspects of the production process and product than were traditionally regarded as parts of the quality control function. These changes have had major repercussions in the field of internal management organization, as well as in the commercial

relationships involved in the procurement of castings. Despite this relatively early appreciation of the need for change, the most significant development came with the introduction of more formal schemes for quality assurance systems, applicable to a wide range of industrial activity and necessitated by the increasingly stringent commercial, legal and technical backgrounds against which casting quality must be judged [32].

For the practical purposes of verification and assessment, however it is useful to think of the quality of castings in terms of two attributes. Firstly the material confers bulk characteristics that are largely reproducible between one piece of metal and another determined by the microstructure associated with the selected composition, casting conditions and heat treatment. These “normal” properties may however, also be affected by some types of disseminated defect arising from impurities introduced in the raw materials or during the foundry process. Indigenous inclusions and dispersed porosity are in this category and can produce common property trends in all the castings in a batch. This “metallurgical condition” can be measured from samples and test specimens intended to be representative of the cast material. The second quality attributes concerns the casting as an individual shape and relates more specifically to the success of the foundry technique. The mold influences the dimensional accuracy and surface finish, and the gating and feeding practice determine the degree of freedom from local defects in the component. This aspect of casting quality is assessed by direct inspection using non-destructive techniques from dimensional measurement to full surface and internal examination [33].

2.5.1 Casting quality assessment tools

Seven basic tools of quality is a designation given to a fixed set of graphical techniques identified as being most helpful in troubleshooting issues related to casting quality. They are called basic because they are suitable for people with little formal training in statistics and because they can be used to solve the vast majority of quality-related issues [34].

The basic tools of quality include: Check sheet, Pareto chart, Ishikawa diagram, Flowchart, Control chart, Scatter diagram and Histogram. Ishikawa diagram and control charts are the two basic quality tools used in this research for quality assessment of steel castings at ABMI.

a) Control chart for demerits per unit (U- chart)

The control chart for demerits per unit (U- chart) assigns weights to nonconformities according to their relative degree of severity [35].

Classification of Nonconformities

Several systems classify nonconformities according to their degree of seriousness. One system, given by the ANSI/ASQC Standard A3 (1978), classifies nonconformities into the following categories.

1. Class 1 defects – **very serious**: defects that lead directly to severe injury or to catastrophic economic loss.
2. Class 2 defects – **serious**: defects that lead to significant injury or to significant economic loss.
3. Class 3 defects – **major**: defects that can cause major problems with normal use of a product or service rendered.
4. Class 4 defects – **minor**: defects that can cause minor problems with normal use of a product or service rendered.

Once a classification of defects or nonconformities has been established, demerits per unit are assigned to each class. Control charts are then constructed for demerits per unit [36].

Construction of a U- Chart

Suppose we have four categories of nonconformities. Let the sample size be n , and let c_1, c_2, c_3 and c_4 denote the total number of nonconformities in a sample for the four categories. Let w_1, w_2, w_3 and w_4 denote the weights assigned to each category. For a sample of size n , the total number of demerits is given by;

$$D = w_1 c_1 + w_2 c_2 + w_3 c_3 + w_4 c_4 \quad (4)$$

The demerits per unit for the sample are given by;

$$U = \frac{D}{n} = \frac{w_1 c_1 + w_2 c_2 + w_3 c_3 + w_4 c_4}{n} \quad (5)$$

The center line of the U- chart is given by;

$$\bar{U} = w_1 \bar{u}_1 + w_2 \bar{u}_2 + w_3 \bar{u}_3 + w_4 \bar{u}_4 \quad (6)$$

Where \bar{u}_1 , \bar{u}_2 , \bar{u}_3 and \bar{u}_4 represent the average number of nonconformities per unit in their respective classes.

The estimated standard deviation of U is given by;

$$\hat{\sigma} = \sqrt{\frac{w_1^2 \bar{u}_1 + w_2^2 \bar{u}_2 + w_3^2 \bar{u}_3 + w_4^2 \bar{u}_4}{n}} \quad (7)$$

The control limits for the U-chart are given by;

$$UCL = \bar{U} + 3\hat{\sigma} \quad (8)$$

$$LCL = \bar{U} - 3\hat{\sigma} \quad (9)$$

If the lower control limit is calculated to be less than zero, it is converted to zero.

2.5.2 Inspection

The inspection process has the dual purpose of ensuring that the product conforms to design requirements and of providing the information needed for quality control. Although foundry production and technical staff are concerned in many aspects of quality control the systematic collection and integration of quality data is frequently channeled through an inspection department, which has a special responsibility for the administration of standards embodied in contracts and commercial relationships. In the latter function the inspectorate is frequently envisaged as being independent of production management. Patently true independence cannot be realized within a single manufacturing organization. Such a principle may in any case be thought to be somewhat at odds with the philosophy of ISO 9000, which would see all from directors to operatives as being concerned with quality as much as with production.

However, an inspector does have special and defined responsibilities with direct accountability to senior management.

2.5.3 Major factors exerting influence on quality of steel castings

The quality of steel castings is determined in global terms. The major factors exerting influence on the quality of steel castings are listed as follows [37].

a) Quality of the molten steel

- Since steel castings have high melting point (1700 - 1800°C, as the information obtained from the operator of the furnace), the quality of the steel is subject to changes, due to the influence of such factors as the chemical composition during the melting-refining process,

the products resulting from the reaction with the refractoriness, the degree of deoxidization, the contents of gas, etc.;

- When the contents of P (Phosphorous) and S (Sulfur) are too large in the chemical composition of the molten steel, the tenacity decreases and the segregation increases;
- When products resulting from the reaction with the refractories are trapped during the solidification of the molten steel, they become inclusions, and they result into reduced tenacity of the product;
- Blow holes may occur in the obtained steel casting when the deoxidization of the molten steel is insufficient;
- When the content of Al (Aluminum) is large, and the content of N₂ (Nitrogen) is large too, the obtained steel casting gets defect in any cause.

b) Quality of the casting mold and core

- Inclusions are prone to be generated within the steel casting as a result of such phenomena as reaction with the refractory, sinterization, infiltration, etc. , that occur during the solidification of the molten metal with high melting point in the mold;
- In order to prevent the said problems from occurring it is necessary to use highly refractory casting sand, and to build the mold by filling the casting sand with an appropriate degree of compactness.

c) Quality of the pouring method

- It is necessary to work quickly and gently way when pouring high temperature molten metal in the casting mold;
- The essential detail of the pouring process is to prevent the flow of molten metal from colliding with the mold and the core;
- It is important to start the pouring process from the bottom of the casting mold.

d) Quality of the casting process

- Steel presents large solidification shrinkage during its transformation from the molten state to the solid state. Such being the case, shrinkage cavities occurs at the parts of the steel casting that solidify in the last place. Depending on the application and the function

of the steel casting, the presence of such shrinkage cavities is not permissible in many cases. (As a general rule, the extent of the solidification shrinkage is of the order of 3%);

- The extent of solid shrinkage that occurs after the solidification is large, and is of the order of 7.2% in terms of volume ratio. The linear shrinkage rate is of the order of 2%, which is approximately twice as large as the value occurring in cast iron. Such problems as hanging rupture, crack, residual deformation, etc., occur concurrently with the shrinkage deformation. These kinds of defects are not permissible in steel castings;
- The strength of the steel casting under high-temperature conditions right below the solidification temperature is low, and cracks are prone to occur due to the internal stress caused by the resistance of the mold and the core during the shrinkage. An appropriate design featuring even cooling (from the design standpoint) and avoiding the concentration of stress is required;
- Solid shrinkage are large, the model shall be made rather large (this is called enlarged scale), so as to make it possible to realize the required dimension and wall thicknesses after the three shrinkage stages mentioned above.

e) Quality of the design

- The changes in the wall thickness occurring in the steel casting shall be minimized, with the object of preventing the occurrence of such problems as shrinkage cavity, crack, etc.;
- Shrinkage cavities, cracks and other problems are prone to occur at parts where the progress of the cooling down process is delayed due to uneven wall thickness. Appropriate measures shall be taken in the design, so as to minimize the occurrence of such parts that are called hot spots;
- The shape of the cross section of a steel casting can be changed with ease in the design, but that result in the occurrence of crack defects when the cooling rate of the casting is uneven. The cause of such defects is the residual stress, and it is necessary to realize even cooling by adopting even wall thickness in the design;
- The shrinkage occurring after the casting depends on such conditions as the material, the shape, the wall thickness, the casting conditions, etc. therefore, the permissible dimensional values shall be taken into consideration in the drawings;

- The steel casting shall be designed in such a way to enhance directional solidification, by taking into consideration the quality and the cost balance. Moreover, at least the items mentioned in the followings must be clearly known when carrying out the concrete quality planning;
- Destination of the product, name of the product, drawing number, specification number;
- Materials, quantity, form of delivery, term of delivery;
- Manufacturing process and manufacturing procedure of the major processes;
- Chemical composition standards and manufacturing target standards;
- Mechanical property standards and procedures for verifying them;
- Heat cycle of the heat treatment, furnace to be used in the heat treatment, and procedure for measuring the temperature must be analysis.

2.6 Porosity prediction in steel castings

A comprehensive methodology that takes into account alloy solidification, shrinkage-driven interdendritic fluid flow, hydrogen precipitation, and porosity evolution has been developed for the prediction of microporosity fraction in steel castings. The mathematical models presented are implemented in a computational framework consistent with those of commercial casting codes, allowing them to be easily incorporated in commercial casting simulation software. Examples are presented for castings of vastly differing solidification behavior. The analysis of:

- a) Metallographic observations of the pore morphology distribution;
- b) Computed solid fraction distribution and
- c) Computed pressure distribution during solidification is used to explain the pore fraction evolution during solidification.

The predictions of porosity distribution are validated by comparison with independent experimental measurements of pore fraction in the test castings.

Attempts to predict the level of porosity in castings have included both parametric and “first-principles” models. A number of other studies have also attempted to understand the phenomena of porosity formation, pore growth and pore morphology.

The governing equations for fluid flow and hydrogen evolution indicate that the porosity formation and fluid flow are strongly coupled. However, in most studies on microporosity, it is

considered that the porosity formation does not influence the fluid flow in the mushy zone. Kuznetsov and Vafai [38] showed that neglecting the effect of porosity formation on the pressure in the mushy zone yields lower pressure drops and an over-prediction of final porosity. They also have shown that the influence of porosity formation on the pressure is larger at lower pressures in the mushy zone.

The methodology for microporosity prediction presented in this study allows the numerical simulation of “hydrogen” and “shrinkage” porosity by considering the following factors that contribute to microporosity formation [39]:

- a) Heat transfer and alloy solidification;
- b) Microstructure evolution during alloy solidification;
- c) Hydrogen redistribution during solidification and
- d) Fluid flow which feeds the solidification shrinkage.

Heat transfer and solidification

Since this work is mainly concerned with the numerical simulation of shrinkage induced flows, the convection term in the energy equation is neglected. The energy equation that describes the heat transfer during alloy solidification appears as:

$$\frac{d\rho h}{dt} + \nabla(\rho_l h_l g_l u) = \nabla(k_{\text{eff}} \nabla T) \quad (10)$$

Where g_s , g_l , and g_g are the volume fraction of solid, liquid, and gas, respectively; ρ_{se} and g_{se} are the density and volume fraction of the solid eutectic, respectively.

$\rho_h = g_l \rho_l h_l + g_s \rho_s h_s + g_{se} (\rho_{se} h_{se} - \rho_s h_s)$ is density weighted enthalpy, u is intrinsic fluid velocity, T is temperature, and $k_{\text{eff}} = k_{sgs} + k_{lgl}$ is effective thermal conductivity. Subscripts s and l refer to the solid and liquid phases, respectively, while subscript e refers to the eutectic phases. h_s , h_l , h_g are the intrinsic enthalpies for the solid, liquid and gas phases, respectively. The temperature is solved by the use of an enthalpy formulation.

Microstructural Parameters

In addition to the liquid and solid fractions, which are calculated from the energy equation, the dendrite cell spacing is needed to estimate pore curvature and permeability in the mushy zone. The dendrite cell spacing, d_c , can be correlated with the local solidification time, t_f , by the use of the following relationship:

$$d_c [\mu\text{m}] = A(t_f)^b \quad (11)$$

Where t_f is the local solidification time in seconds. For steel, the coarsening constants are determined from published data, as:

$$A = 10.2 \text{ and } b = 1/3 \quad (12)$$

Hydrogen Balance

It is commonly accepted that pores form in solidifying aluminum alloys when the equilibrium partial pressure of hydrogen corresponding to the hydrogen concentration within the liquid, exceeds the local pressure in the mushy zone by an amount necessary to overcome surface energy forces [39]. Thus, the condition for microporosity formation can be given in terms of a pressure condition as described in equation (1). Equation (1) is only used to provide the condition for a hydrodynamic balance of pressure in the region of a bubble. Since the molten metal used in most foundries has a high concentration of oxide films that serve as nucleating substrates for hydrogen bubble nucleation, detailed models of bubble nucleation may be neglected.

By using Sievert's law to relate the hydrogen concentration in the liquid to the gas pressure, P_g (atm), and neglecting hydrogen diffusion, the hydrogen distribution is described by the following mass balance:

$$f_g C_H^u = C_H^0 - S\sqrt{P_g} (f_s k_H + f_l) \quad (13)$$

Where C_H^0 is the initial gas concentration within the liquid (cc/100g), S is the hydrogen solubility in the liquid (cc/100g), $k_H = 0.069$ is the partition coefficient for hydrogen distribution between solid and liquid, f_s and f_l are the mass fractions of solid and liquid, respectively. C_H^u is a unit conversion factor from cc/100g to mass fraction.

Interdendritic Flow and Microporosity

In order to accurately predict microporosity, a solution algorithm for interdendritic flows in which the coupling between pore growth and liquid feeding is treated implicitly is used in this study. The solution algorithm for interdendritic flows is based on a variable projection method and is extended in this study to include the effect of microporosity on the interdendritic flow. In this methodology, the energy and microporosity equations are uncoupled. The energy equation is solved by using the hydrogen gas fraction at the previous time level, g_g^n , without considering the effect of pore growth within the current time step.

$\rho^{*n+1} = \rho_l^n g_l^{*n+1} + \rho_s g_s^{*n+1} + g_{se}^{*n+1} (\rho_{se} - \rho_s)$ is the density which is estimated based on volumetric fractions g_l^{*n+1} and g_s^{*n+1} computed from the energy equation.

2.7 Porosity control and reduction methods

The most known methods for the control of the porosity are [40]:

1. X-Ray;
2. Cutting the parts and polishing the section of the part and for analyze using a microscope;
3. Computerized tomography.

The most common methods are the first two. As state of the art the computerized tomography for the analysis of the porous defects in castings the volume and localization of the porosities can be precisely determinate and built in numerical 3D models.

The simplest way is to do a good process definition and setup since the beginning and to keep it under control by assuring the stability of the process. The stability of the process can be assured by keeping under control the process parameters.

2.8 Porosity analysis methods

At a late stage during solidification, liquid metal from the feeder will need to flow through the pasty zone to compensate for the contraction as an increasing amount of solid metal is formed at A. As the contraction tries to pull liquid metal through the pasty zone, it imposes a tensile force upon the liquid. One analogy for this is to imagine that a long elastic rope is being pulled through a forest of trees; it can be imagined that the tortuous route leads to friction along the length of the rope. The elastic rope stretches increasingly towards the direction of the applied pull. This is analogous to the liquid, which is stretched elastically, and experiences an increasing tensile stress as it progresses through the dendrite forest of the pasty zone.

This situation can be analyzed in various ways. The easiest approach is to assume that the pasty zone is uniform, and then use the famous equation by Poisseuille which describes the pressure gradient required to cause a liquid to flow along a capillary. This shows a capillary of radius r with pressures of P_1 and P_2 at each end over a distance of L through which a liquid is flowing at a volumetric rate of v per second. Fairly simple calculus can be used to show that:

$$P_1 - P_2 \propto L\eta v / r^4 \quad (14)$$

Where η is the viscosity, this clearly shows that the resistance to flow is critically dependent on the size of the capillary.

In the case of a liquid metal flowing through a capillary, it is simultaneously solidifying and therefore slowly closing the channel. An approximate solution of this situation gives:

$$\nabla P \propto \eta L^2 / r^4 \quad (15)$$

This shows that the pressure drop by viscous flow through the pasty zone is still very sensitive to the size of the flow channels. L is the length of the pasty zone in the casting and is equal to the whole casting length in most aluminum castings since the thermal conductivity is high and the temperature gradient consequently low. The dendrite arm spacing, DAS, is a measure of the interdendritic flow channel diameter ($= 2 \times r$)[28].

CHAPTER THREE: MATERIALS AND METHODS

3.1 Materials

The cast pinion gear, drive disc and head stoke components are made of manganese steel of low carbon content with composition of C: 0.25 - 0.35%, Mn: 0.6 – 0.8%, S: 0.05%, P: 0.05% and Si: 0.6%. Composition analysis is made using spectrometer which obtained at Akaki Basic Metals industry. In addition different materials which obtained at Akaki Basic Metals industry have used for this research. These include washed and dried silica sand, no-back binder which composed of resin, catalyst and additives, paint that has to be applied on the pattern for easy removal of the pattern from the mold, steel of varying grade, wood for making pattern and water to test the clay content of the silica sand.

3.2 Methods

The following methods were implemented in in this research.

- Data collection: data gathered from both primary and secondary sources (interviews and discussion with individuals who actively involved in the topic area of the research and concerned people);
- Direct physical observation at the industry;
- Experimental analysis by taking different measurements of the selected defective components of Manganese-steel;
- Photographs with the help of digital camera were used to obtain information for the defect analysis.
- Both qualitative and quantitative analyses are performed to analyze the effect of porosity on the selected defective components.

3.3 Equipment, Machines and Tools

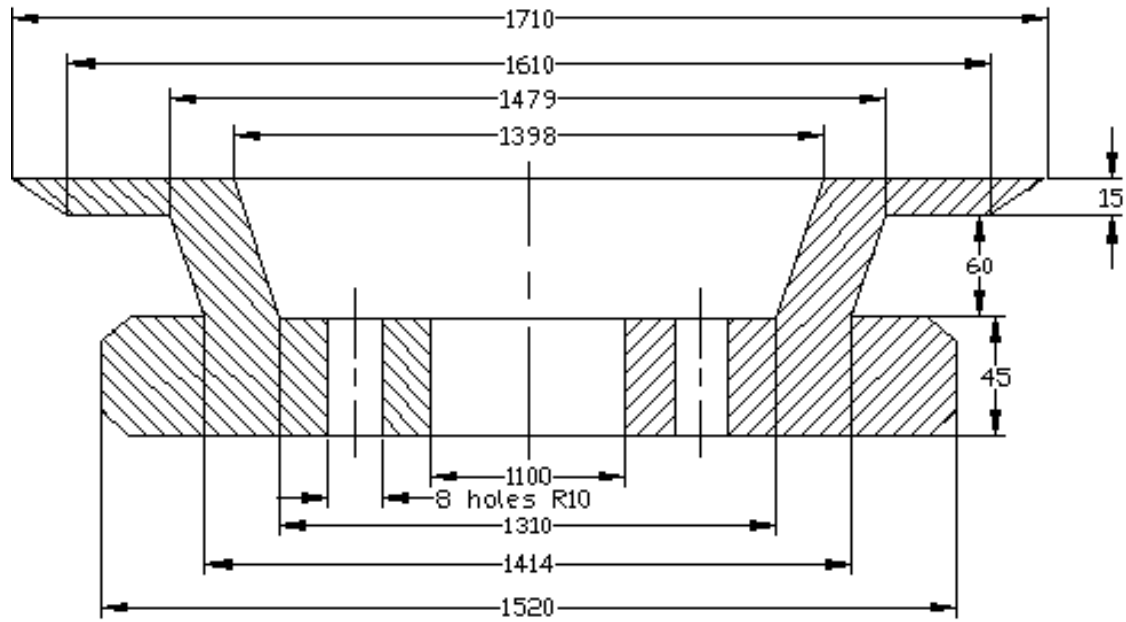
The equipment, machines and tools for this research were sourced and provided by the foundry shop of Akaki Basic Metals Industry. These equipment, machines and tools are used in sand preparation, molding, melting, pouring, during solidification and separation of the casting from the mold. These include; sieve analyzer, clay content tester, metal melting equipment (medium frequency induction furnace), fettling and finishing equipment, spectrometer, wooden rammer, pyrometer, wooden pattern and vernier caliper.

3.4 Sample and sample preparation

It is not feasible to obtain data regarding a certain quality characteristic for each item in a population due to lack of time and resources. Furthermore, sample data provides adequate information about a product or process characteristics. Akaki Basic Metals Industry has main responsibilities to produce different metallic components for various factories and industries of the country. But it is suffering from quality related problems of casted products with some reasons. Some of the defective components of the industry include large gears, head stock components, trash plates, scraper plates, flanges, rollers, wheels, pulleys, sleeve liners, pinion gears, and sprocket gears of steel. Among these defective components the pinion gear, drive disc and head stock components of manganese steel are chosen for this research as a sample by cluster sampling method.

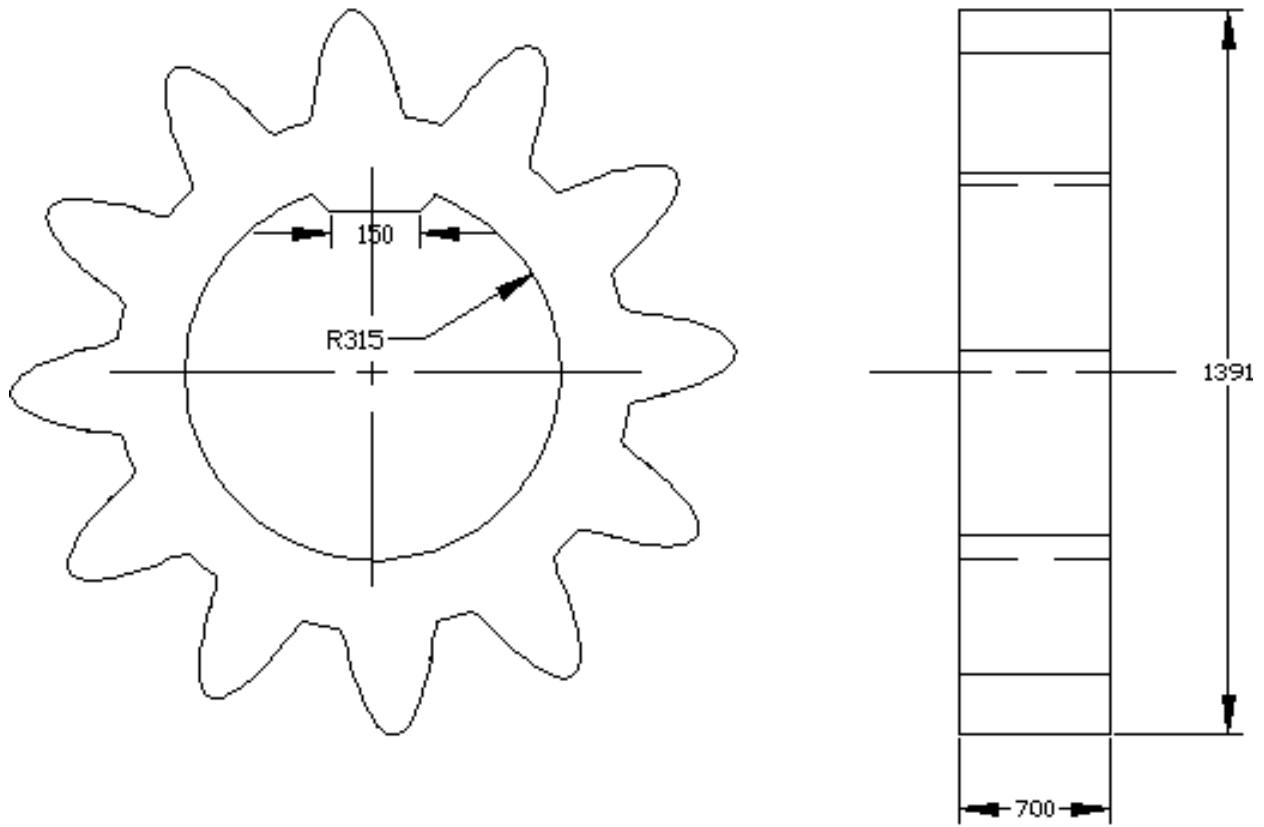
Figure 11 shows the sectional front view of the defective drive disc component and Figure 8 show the schematic diagram of the pinion gear which are manufactured by sand casting process (no-back system of mold making) from Manganese steel. The chemical compositions of the defective components are shown in Table 7. Sample pores were taken from the surfaces of the defective components. A total number of 100 pores were collected. The depth and diameter of the sample pores were measured by using Vernier caliper of 0.01mm accuracy. Pores were owing to a subsequent machining and grinding process after casting. The photographs of the surface of the defective components were taken with the help of digital camera. Then, images were imported into a personal computer and photographic analysis has given.

The sample pores were grouped in four classes based on their seriousness as very serious, serious, major and minor. The weights given for very serious, serious, major and minor nonconformities by American Society of Quality Control are 100, 50, 10 and 1 respectively. Control charts for number of demerits per unit (U-charts) were constructed for both nonconformities in pore depths and diameters to determine whether the process is in control or not. The Ishikawa (fishbone or cause and effect) diagram has used to show the main causes and sub causes to effect porosity. The desired dimensions, the actual dimensions (after casting) were measured. The reduced dimensions from the surfaces of the defective components for the purpose of avoiding pores and cavities were determined.



(All dimensions in mm)

Figure 11: Sectional front view of the drive disc selected for analysis



(All dimensions in mm)

Figure 12: Schematic diagram of the pinion gear selected for analysis

CHAPTER FOUR: DATA COLLECTION AND EXPERIMENTAL ANALYSIS

To carry out this study various data collecting methods including interview, physical observation, photographic methods as well as experiments were conducted. The case as mentioned earlier was considered on the cast products of Akaki Basic Metals Industry. Akaki Basic Metals Industry is producing its products in four different sections. These four sections are the foundry workshop, mechanical workshop, hand tools, cutlery and forging and heat and surface treatment. Among these the foundry and machine workshops have been observed and the employees of this industry particularly the foundry people were interviewed randomly. Besides this the production processes of each shop were observed. Based on this, steel casting quality related problems (defects), specifically porosity defect and production related data were collected from the two sections of the industry.

4.1 Background of Akaki Basic Metals industry

Akaki Basic Metals Industry (ABMI), in its previous name Akaki Spare Parts and Hand Tools Share Company (ASPSC) is one of the biggest job order manufacturing companies in Ethiopia. It is located in the south-east direction at 22Km from Addis Ababa adjacent to the main road to Debrezeit. It started operation in 1981EC. The main objectives of the industry's establishment are:

1. Supporting local factories and industries by supplying various spare parts and machinery components. Some of the assumed factories and industries to get the products from ABMI include:
 - a. Textile factories
 - b. Sugar factories
 - c. Cement factories
 - d. Transportation sector
 - e. Addis Tire and others
2. By supplying spare parts from local factory, it was intended to save foreign exchange of the country and to minimize waste of time in long lead-time.
3. Enhancing the development of Metal Sector in the country:

There are different metal processing public and privately owned factories in Ethiopia. Most of them were established prior to ABMI. Almost all of these factories are limited to machining, sheet metal fabrication and assembly works with very limited capacity. Before the establishment of ABMI, no metal processing plant of Ethiopia had foundry workshop of steel and cast iron. Automotive Manufacturing Company of Ethiopia (AMCE), the only automobile assembly plant of the country, at the time, has no in house capacity to produce parts for its assembly. Therefore, ABMI was established with almost all rounded capacity to give useful support to the development of these infant factories.

The industry has fixed capital of \$83,381,000. Presently, about 600 workers are employed but at full capacity, it can employ 900 workers. It is established on a total area of 155,000m² of which 30,500m² is covered. At ABMI, the foundry section is large work shop which is equipped with different equipment facilities and arrangement. The floor area of foundry work shop is 5376m² it comprises of both ferrous and non-ferrous melting units. Both units can cast 4500tons in two shifts annually. The furnace capacities of both units are as follows:

- The ferrous foundry has 3 induction furnaces each with a melting capacity of 3.3 tones and one furnace with melting capacity of 250kg. The various materials produced in the ferrous foundry include nodular cast iron, white cast iron, gray cast iron, Low carbon and alloyed steels as per the customer's requirement.
- The non-ferrous foundry have Aluminum resistance furnace (500kg), Bronze resistance furnace (500kg), Holding furnace for aluminum 500kg.

In this study the ferrous metals foundry shop is the main concern. Problems associated with quality of cast manganese steel products will be studied. This study aims to find the defects in manganese steel castings, analyze these defects and providing their remedies.

The foundry workshop is used to cast different metal products and supply to the next workshop for further machining or to the finished goods store for sale. In other words castings are the large input materials for the rest of the shops at ABMI. The units and sub-shops, which are under foundry workshop, are shown in the organizational structure of ABMI in Figure 13.

ABMI produces various types of metallic products. Its main products can be classified into four major groups. These are:

- i. **Machines and sheet metal products** such as wood lathe machines, double end grinding machines, sheet metal rolling machines, sheet metal shearing machines, cold press machines, water and fuel tankers, and high and medium tension electric cable carrying hooks and pins;
- ii. **Spare parts of different machines** such as shafts, rollers, sleeves, gears, sprockets, coil springs, sugar mill rollers, ingot molds, scraper plates, trash plates, armor plates, cement balls, various types and sizes of cast and machined products;
- iii. **Industrial hand tools** such as wrenches, pliers, screw drivers, hammers, cutters and other hand tools and
- iv. **Cutlery** such as forks, spoons and knives.

Among the various types of the industry's products, some are frequently ordered by customers and they are treated by the industry as selected products. As they are economically useful both to the industry and to the customers, they are given special attention. The estimated annual production capacity of the industry for some selected products, among a number of them, is shown in Table 7.

For better understanding of the company, the organizational structure of the company is shown in Figure 12. As the organizational structure shows, the direct production area of the company is divided in to four divisions. These are:

1. Foundry Workshop , FWS
2. Mechanical Workshop, MWS
3. Hand Tools, Cutlery and Forging, HCF
4. Heat and Surface Treatment, HST

All the four production divisions and two additional supporting divisions (Design, Production Planning and Control (DPPC), and Maintenance) are under the supervision of manufacturing department.

Table 7: Annual production capacity of ABMI for selected products

No.	Product name	Customer	Annual Production Capacity (Pcs)	Estimated production cost	
				Unit	Total
1	Sugar mill roller	Sugar factories	40	88,920.00	3,556,800.00
2	Trash plates	Sugar factories	50	9,800.00	490,000.00
3	Scrapper plates	Sugar factories	55	4,550.00	250,250.00
4	Draw bars	Sugar factories	3,000	1,372.00	4,116,000.00
5	Headstock	Sugar factories	4	241,984.25	967,937.00
6	Pinion gear	Sugar factories	45	52,634.54	2,368,554.30
7	Liner plates	Cement factories	2,400	995.00	2,388,000.00
8	Drive disc	Cement factories	50	47,524.64	2,376,232.00
9	Brake drum	Transport sector	1,200	1,925.00	2,310,000.00
10	15Kv hooks	EEPCO	130,680	21.95	2,868,426.00
11	N-95 hooks	EEPCO	232,320	6.90	1,603,008.00
12	N-80 hooks	EEPCO	232,320	5.70	1,324,224.00
13	33 Kv pins	EEPCO	72,600	23.70	1,720,620.00
14	Termination sleeve	Ethio-telecom	390,000	9.20	3,588,000.00
15	Distribution support	Ethio-telecom	400,000	31.30	12,520,000.00
16	Stay rod	Ethio-telecom	120,000	65.00	7,800,000.00
17	Central support	Transport Sector	2,500	2,089.00	5,222,500.00
				Total	55,470,551.30

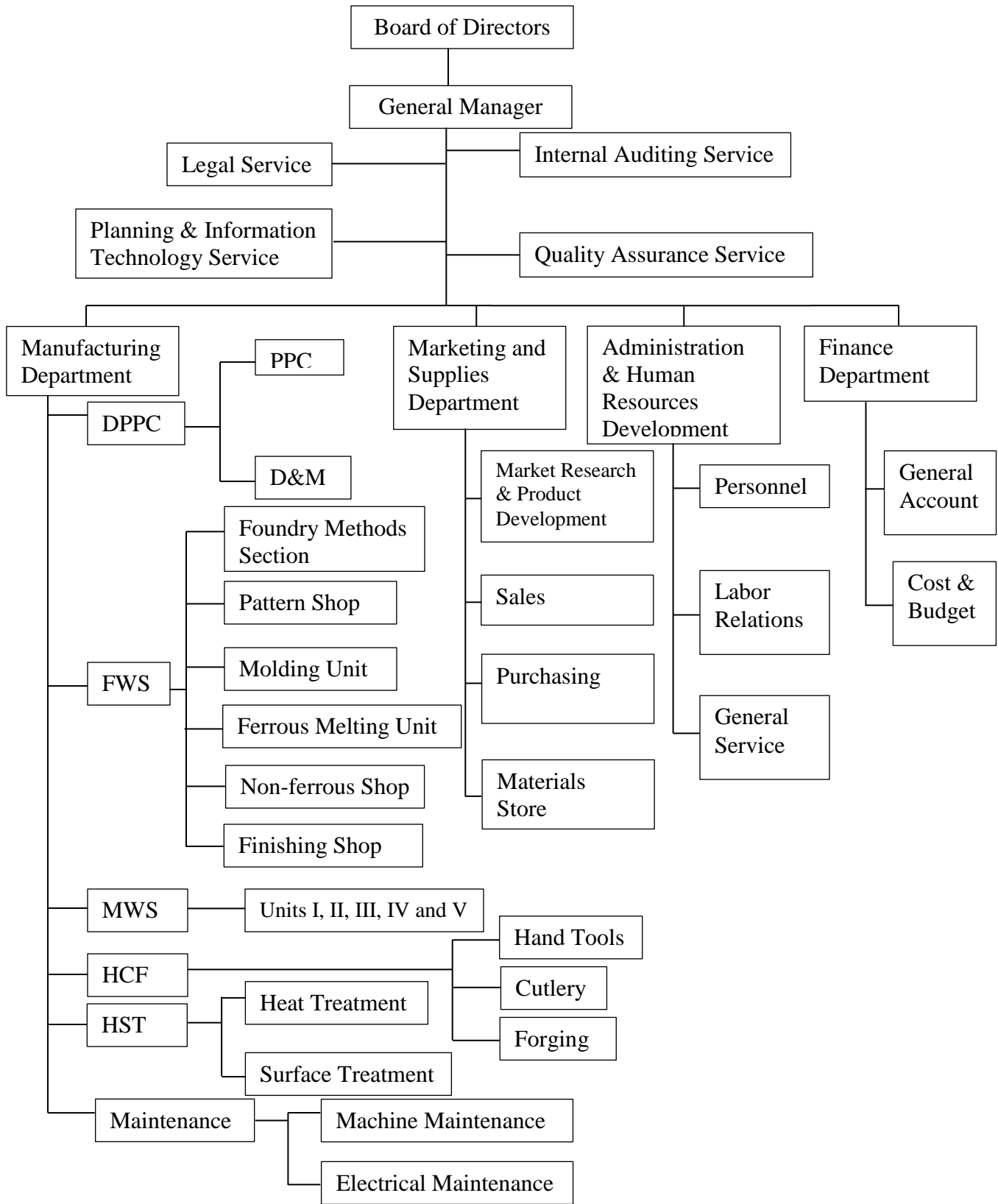


Figure 13: Organizational structure of ABMI

Casting method used to produce the pinion gear, drive disc and head stoke components were sand casting. For mold making dry silica sand reclaimed and furnished with fresh sand that were bonded with furan resin (no bake system of mold making) was used. Manual (wooden) rammers and/or hand ramming were used to pack the silica sand around the pattern. The gating system while pouring has made was from the bottom for the pinion gear, side for the drive disc and headstoke components through the riser. Induction furnaces of medium frequency were used for melting and pouring was carried out by using the old ladles. The riser constructed was cylindrical in shape located in a vertical position. After casting the parts were separated from the mold by shaking out and removing of the sand from the surface of the parts. Grinding and machining operations were performed for fettling process. After grinding and machining, visual examination and measurement of the pores using Vernier caliper of 0.01mm accuracy were carried out. 100 randomly selected defected points were taken and their depths of penetration and diameter were measured using Vernier caliper. In addition photographs with the help of digital camera have made to obtain information for the analysis. Detailed analysis of the data obtained was made as follows.

A) Observation

The cast pinion gear, drive disc and head stoke components are made of manganese steel. The composition of each component is given in Table 8. Composition analysis was made using TREC� portable solid spectrometer of 4mm minimum sample thickness handling type which is available at Akaki Basic Metals industry and is specifically used for ferrous metals.

Table 8: Materials used in steel castings

Part	Material	Composition				
		C	Mn	S	P	Si
Pinion gear	Manganese steel	0.25 - 0.35%	0.6 - 0.8%	Max. 0.05%	Max. 0.05%	Max. 0.6%
Drive disc	Manganese steel(46MnSi4)	0.42 - 0.5%	0.9 - 1.2%	Max. 0.04%	Max. 0.04%	0.7 - 0.9%
Head stock	Manganese steel	0.25 - 0.35%	0.6 - 0.8%	Max. 0.05%	Max. 0.05%	Max. 0.6%

Manganese steels have extensive application in steel industries due to good resistance to wear associating with high impact strength, high work hardening capability with high toughness and ductility. Moreover manganese steels have good castability [29]. As the information obtained from the industry, the main reasons for the selection of Manganese steel for casting purpose at ABMI include:

- The material gives a wide range of flexibility when we process in casting steel products;
- Freedom for casting;
- Fewer defects creating probability when we compare to the other steel casting material;
- If the percentage of carbon content is increases the tendency to develop defect is lower as compared to the material which have lower amount of carbon content.

In addition to this, Manganese steel has some special properties that make it irreplaceable. In technical practice the hardenability by high static or dynamic stress is used. The high hardness of face layers increases the abrasive wear resistance but because the middle part keeps good toughness, the components support high impact stress.

B) Interview

As the information obtained from the industry, the pinion gear and drive disc may face wear failure since they are subjected to rotational motion and there will be friction of these components with contacting drive and driven parts which may lead to wear failure. So it is necessary to have good wear resistance property for the pinion gear and drive disc. On the other hand the head stoke is subjected to high compressive stress. The purpose of the head stoke is to carry very large and huge rollers, gears and other heavy components in horizontal position. Generally speaking all the three components should have to be defect free especially free from porosity to serve their intended purpose. But the defective headstock components are assembled and submitted to the respective customer while defective components are available and their quality level is taken as accepted by ABMI. No repairing action was taken or blow holes and cavities were not filled by welding operation. The quality level of the pinion gear is taken as acceptable. Filling of the shrinkage cavity with similar material is done by welding process and pores are avoided from the surface of the pinion gear by grinding and machining operations. No decision has been made on the drive disc (neither accepted nor rejected at the time when this research was conducted). Other

information obtained by interview are provided in different sections of the paper in a more organized way.

C) Experimental data

4.2 Molding methods and materials

4.2.1 Sand used at Akaki Basic Metals Industry

The mold material used in the foundry shop of ABMI is silica sand as the information obtained from the employees of ABMI and observations made in the industry. The type of mold that is applied for casting process is collapsible type; it should be fragmenting after each process concluded. The sand used is composed of two constituents: new and reclaimed sand.

a) New sand

Sand brought from the quarry in general and from Jemma valley in ABMI case is currently washed manually and deposited on concrete silos on the ground floor via a hopper vibrator bucket elevator and belt conveyor. The new sand stored in silos can either be transported to the hand molding (HM) and mechanized molding (MM) or to the regenerated sand silos via the cooler of the hot recycle.

b) Reclaimed sand (Mechanical Reclamation)

After pouring molten metal in to the mold, the mold is allowed to cool for a reasonable time following which it is transported in to the operations of separating the casting and the mold, shot blasting, sand reclamation and separation of shots and for recirculation is carried out.

Since the molds are prepared by hand ramming, the strength of the mold is not sufficient enough. The weakness of the mold walls may lead to erosion of the mold during pouring and also may cause other defects like sand sintering, mold penetration and burn on.

The first major stage in founding is the production of the mold, with its impression of the casting and its planned provision for metal flow and feeding. For this purpose a pattern is required, together with foundry equipment ranging from molding and core making machines to molding boxes and hand tools. A simple wooden pattern was used to produce the pinion gear, drive disc and head stock components at ABMI. Among the five major allowances given for the pattern as discussed in the literature review, only the machining and draft allowances were considered

during the production of the selected components. This leads to rejection of parts due to formation of defects and unsatisfactory design requirements of products.

It should be emphasized that the molding procedure for a particular casting is largely determined by the means chosen at the outset for pattern removal and embodied in the construction of the pattern. For this reason decisions as to the entire manufacturing technique should be taken at the earliest stage including consideration of the orientation of the casting for gating and feeding as well as for pattern withdrawal. A rational choice can then be made of the system of parting lines, cores and other features to achieve overall economy in manufacturing. A further decision which greatly influences production costs concerns the size of mold unit to be adopted and the arrangement of patterns in relation to mold dimensions. The nature of the molding practice is closely related to the molding material employed. When the molten metal enters the mold, the mold reacts violently. The survival of a saleable casting is only guaranteed by the strenuous efforts of the casting engineer to ensure that the molding and casting processes are appropriate, and are under control. But from the observations at ABMI there is no careful attention for these issues. Only those aspects of the mold preparation to create cavities of desired shapes of casting are considered that introduce defects and results in rejection of parts and high production cost due to rework.

Akaki Basic Metals Industry is using dry sand (no bake molding system) for mold making. The sand type silica sand (SiO_2) which comes from Jemma Valley (around Debre Birhan) currently used at ABMI has the following specification.

- Color: white - light brown
- Fusion point: $(1427 - 1760)^\circ\text{C}$
- Grain Fineness Number: (40 - 80)
- Clay content: (0 - 1.5)%
- Silica content - (94 - 99)%

There are no measures taken to test very important properties like permeability of the sand for sound casting based on standard value. Only the clay and moisture contents are the main concerns at ABMI.

4.2.2 Binders

The resin used at ABMI is Furan resin which mainly uses Furfural alcohol (FA) of the following specification.

- Furfural Alcohol: $80 \pm 3\%$
- Free formaldehyde content: Maximum 0.1%
- Water content: 0.5-1.0%
- Storage life: at 20°C , 12 Months
- Viscosity: at 20°C : 10MPa
- Density : at 20°C : 1.135 gm/ cm^3 - 1.15 gm/ cm^3
- Flash point: 68°C
- Fewer odors
- To be used in a continuous mixer

Specification of the Catalyst

- The catalyst can be phosphoric or sulphuric acid
- Density: at 20°C , 1.23 gm/cm^3
- Storage life: unlimited

Furan system

The resin used in these processes is mainly used on Furfural alcohol with the FA content being (50 - 70) %, the resin is virtually viscostatic. Mixing the sand and catalyst must take place in a continuous mixer, the acid being added to the sand before the resin. The resin/acid cold setting system is the area of foundry technology where currently the development is the greatest with strip time being reduced to as low as (30-60) sec to make it suitable for high speed production of small cores or up to 30min for large molds and cores. Resin can be produced with a wide range of viscosities to suit climatic conditions. Variation of temperature of sand can also be compensated for by changing the strength of the catalyst to give the same setting time.

The reason to select the no-back binder system, furan resin at ABMI includes its ease of shake out, good tensile strength, good flowability, excellent erosion resistance and other important properties indicated in Annex C.

4.2.3 Proportion and calibration of chemicals

The metal to sand ratio used at ABMI is 1:5. This means if the weight of the metal to be cast is 100kg we use 500kg of sand for mold preparation. And for the molding we use 1.2% resin (example for 100kg of sand we use 1.2kg resin) and 0.6% catalyst (example for 100kg of sand we use 0.6kg catalyst).

4.3 Melting procedure

4.3.1 Melting furnaces

In the foundry shop of ABMI, a number of different materials are cast including cast iron and its alloys, steel and its alloys, copper alloy castings and aluminum castings and the melting furnace used for the purpose are as described in Table 9.

Table 9: Melting furnaces at ABMI and their capacity

Furnace type	Material type	Quantity	Holding capacity (Kg)
Medium frequency induction furnace	Ferrous metal	3	3300
Medium frequency induction furnace	Cu-alloys	1	500
Electric resistance Furnace	Al-alloys	2	500
Induction furnace	Ferrous metal	1	250

Induction furnaces of medium frequency were used for melting the metal during the production process of the cast pinion gear, drive disc and head stock components. Not only these components; the medium frequency induction furnace is used to melt all types of cast irons and steels and their alloys. The process of melting steel in induction furnaces consists of charging the furnace with steel scraps and melting it down. Melting is quite rapid, so much so that there is only a slight loss of the easily oxidized elements. As soon as melting is complete, the desired super heat temperature is obtained and the metal is deoxidized and tapped in to ladles. Charge is usually carefully selected from scrap and alloys of known composition so as to produce the desired analysis in the finished steel. Chemical analysis of the metal is conducted after complete meltdown and before tapping and slight adjustment by the addition of carburizer or Ferro-alloys can be made. The fact that high alloy metal can be remelted in these furnaces with a slight loss of

the alloy content through oxidation (such as high manganese steel melting) makes it a particularly valuable melting furnace. Since very high temperature is involved in the melting of steels, (up to 1650 °C) refractory materials with high refractory values are used to line the furnace. In the case of the foundry shop of the ABMI, (Al₂O₃) refractory materials in powder form are used to line the furnace, through the process of ramming and controlled sintering process is necessary.

Pyrometer is used in order to know the melting temperature of the metal by the color of the melt using infrared ray.

The steel furnace operator shall attempt to regulate conditions so that the steel is up to pouring temperature when all control processes are conducted. Temperature control is important in that a cold heat would lead to misruns or the loss of an entire heat. During tapping of clean heat into ladles, deoxidizers, such as Aluminum piglets are added to the ladle to deoxidize the heat.

The melting process at ABMI includes;

- Charge adjustment
- Melting
- Tapping (furnace to ladle) and
- Pouring

Preconditions which may takesplace in the selection of the scrap (handling of the scrap) are

- Water free
- Grease free
- Purity from other dirt and dust

Tapping depends up on the following points.

- Mass of the melt
- Number of molds to be filled
- Size of the mold

4.3.2 Deoxidation and tapping

When the molten steel is ready for tapping, a deoxidizing agent is added to remove the oxygen dissolved in the liquid steel. This also ends the removal of carbon by oxidation in to carbon monoxide bubbles. The common deoxidizers are ferromanganese, ferrosilicon and silicon-

manganese. After about ten minutes, the molten steel can be tapped into ladles. The steel is deoxidized further in the ladle just before pouring. Ladle deoxidation is done with ferrosilicon and ferromanganese or with aluminum. Use of aluminum results in fine grained steel. Carbon content can be increased, if required, by adding petroleum coke to the molten steel in the ladle.

4.3.3 Pouring temperature

The pouring operation is started at high temperatures in the case of multiple pouring of small-sized steel castings, and on the other hand high-temperature pouring operation is carried in the case of large-sized steel castings. There is no direct correlation between the pouring temperature and the generation of bubbles, the maximum melting temperature exerts influence on the generation of bubbles. It must be remembered however, that there is less occurrence of shrinkage cavity when the pouring temperature is low within practical limits. As for the relationship between the pouring temperature of the steel billet and the cracks, an increase of cracks is observed from 1538⁰C, and a substantial increase occurs with a rise of 55⁰C in the temperature. Concurrently with the tapping the temperature of the molten steel lowers from the value prevailing in the melting furnace due to the heat loss caused to the tapping and then it lowers still more in the pouring ladle. Thus, the pouring temperature must be determined by taking into consideration the said facts.

4.3.4 Solidification time and temperature

ABMI doesn't have a well-controlled solidification time. It has done by trial and error. There is no identification even for the material type and the condition of solidification process. The solidification time is simply given a by the weight of casting not actually relate by material and other related factors which is responsible for the property of the product. So that the exact solidification or temperature control is such initiative in order to obtain good quality of casting. One can say that a good quality of casting is obtained when good metallurgical property, size and shape, microstructural arrangement and fulfilling of design requirements are achieved. But without a well-organized solidification and temperature control it is impossible to get sound castings.

4.4 Casting design

Casting design is carried out with two objectives

- To achieve desired internal soundness in casting
- To evolve a design which reduces molding, cleaning and machining cost.

The importance of design engineers and foundry man working together at the design stage itself is emphasized.

4.4.1 Riser design for the pinion gear

1. Weight determination

The part is sketched on the computer with the aid of AutoCAD software. This software provides the net weight reading based on the total area and height of the part.

Therefore the net weight of the pinion gear is obtained as 4784kg.

The gear is made of Manganese steel that has a density of 7860kg/m³.

2. Yield preparation (Gross weight determination)

Gross weight = weight of sprue + riser + in gate + the casting object

Standard yield preparation:

- For steel 40-60% = yield (sprue + riser+ in gate)
- Considering 55% weight of sprue + riser + in gate (yield) i.e. the remaining 45% is the weight of the part to be cast.

Thus the gross weight for the pinion gear becomes

$$\begin{aligned} \text{Gross weight} &= \frac{\text{net weight}}{\% \text{ yield}} \\ &= \frac{4784\text{kg}}{55\%} = 8698 \text{ kg} \end{aligned} \tag{16}$$

Gross weight = Net weight + Return

Return = Riser + sprue + other (ingrate + runner)

8698kg = 4784kg + return

Return = 3914kg

From standard sprue + other (ingrate + runner) = 20kg max

Riser = Return - 20kg max = (3914 - 20) kg = 3894 kg

3. Volume of the riser

$$V_{\text{riser}} = \frac{\text{Mass of riser}}{\text{Density of riser}} \quad (17)$$

$$= \frac{3894 \text{ kg}}{7860 \text{ kg/m}^3} = 0.4954 \text{ m}^3$$

Riser diameter (D) and height (H)

The riser used to produce the pinion gear is cylindrical in shape.

Volume of a cylinder = Area * Height

$$V_{\text{cylinder}} = \pi D^2 H / 4 \quad (18)$$

The recommended value of H at ABMI is

$$H = 1.5D$$

$$V_{\text{cylinder}} = \pi D^2 * 1.5D / 4$$

$$0.4954 \text{ m}^3 = 1.5\pi D^3 / 4$$

Therefore D = 750mm and H = 1125mm.

Large diameter and height of a riser can be compensated by increasing the number of risers. Hence let's use four risers rather than using a single riser.

Therefore D = 750mm/4 = 187.5mm and H = 1125/4 = 281.5mm

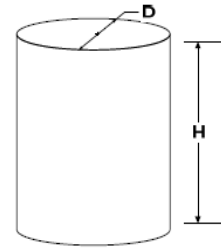


Figure 14: Schematic diagram of a cylindrical riser

4. Pouring time (t) depending on gross weight

$$t = S_4 (Tw)^{1/3} \quad (19)$$

S_4 is a correction factor depending up on mean wall thickness (100mm) and almost taken as 1.

$$t = S_4 (8698 * 100)^{1/3}$$

$$t = 95.5 \text{ seconds}$$

5. Chock area

$$\sum A_i = \frac{G}{0.317 \mu t \sqrt{H}} \quad (20)$$

Where G is the gross weight

t is the pouring time

μ is the coefficient of friction (0.2 – 0.8)

H is the height of the flask on the cope side (height of the riser)

$$\sum Ai = \frac{8698\text{kg}}{0.317 \times 0.25 \times 95.5 \text{sec} \sqrt{2.815\text{cm}}} = 342.64\text{cm}^2$$

Diameter (D_n) and length (L_n) of neck

Diameter of neck (D_n)

$$D_n = 1.2L_n + 0.1D \tag{21}$$

Where: L_n = Length of neck

D_n = Diameter of neck

$$L_n = L_{\text{max}} = D/2 = 187.5/2 = 93.75\text{mm (maximum)}$$

$$D_n = (1.2 \times 93.75\text{mm}) + (0.1 \times 187.5\text{mm})$$

$$D_n = 131.25\text{mm}$$

6. Sprue design:

Chock area = 342.64cm^2 = ingate value

Ingate, runner and sprue ratio for steel = 1:1.2:1.6

$$\text{Runner} = 1.2 \times 342.64 = 411.17\text{cm}^2$$

$$\text{Sprue} = 1.6 \times 342.64 = 548.22\text{ cm}^2$$

4.4.2 Gating system

The term gating or gating system refers to all the passages or channels through which the metal enters a mold. The system may be simple, for instance, as in pouring the metal straight into the mold through a hole in the cope as shown in the figure below.

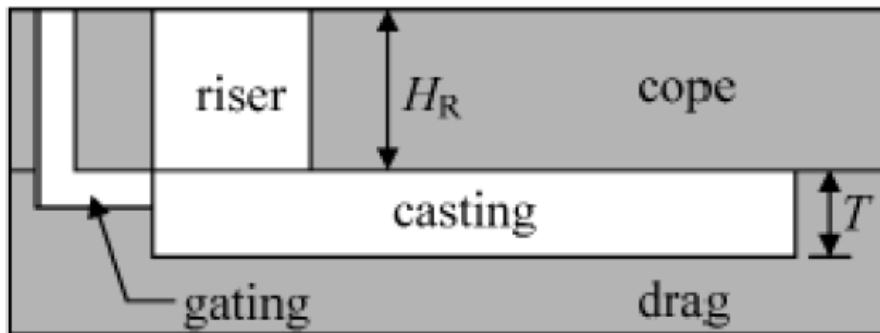


Figure 15: Schematic diagram of the gating system

It has been seen that the gating system at AMBI suffers the following problems.

- The metal flows through the gating with maximum turbulence. There is very high aspiration or sucking of the gasses which may lead to formation of bubbles and porosity defect;
- The weight of the gates is large due to improper implementation of the casting designs so that the casting yield is maximized;
- The mold cavity is not completely filled by the molten metal in accordance with the calculated pouring time. There is no proper control of the pouring time. Pouring has been done traditionally;
- Erosion of the mold due to weak mold strength that results from inappropriate hand ramming.

Of these, the first is the most important. The first and third points are mutually opposing requirements; fast filling to reduce the time may involve very high velocities of the metal stream and turbulence. A compromise has to be made between the two objectives.

System components

A gating system in general; may involve the following components or sub-systems:

- Pouring basin or cup
- Sprue
- Runner and
- Gates.

Sprue system process

When the molten metal is taken with the ladle and poured in the casting mold, it passes through the sprue, the runner and the gate before entering into the casting mold. The route through which the molten metal flows into the casting mold, the size and the shape of the passageway, the flowing speed of the molten metal, and the refractory material of the passageway are factors that exert remarkable effect on the quality of the product.

According to Japan Iron and Steel Association, the casting defects caused by the sprue system are broadly classified as shown in the followings:

1. Formation of sand inclusions caused by the content of the metal with the casting mold wall;
2. Formation of inclusions due to the oxidization caused by the air during the pouring process;
3. Formation of inclusions due to the mixture of products of the deoxidization process;
4. Formation of oxide type inclusions due to the reaction with the refractory;
5. Mixture of the slag;
6. Formation of surface fold (elephant skin) and misrun due to insufficient pouring temperature and pouring speed;
7. Formation of pull down due to insufficient rising speed of the molten metal surface.

As it has seen from the casting defects mentioned above, however good is the model process, the casting process, the molding process and the steelmaking process, it becomes impossible to manufacture steel castings of superior quality if the sprue process is not appropriate.

4.5 Effect of pore sizes on the dimension of the pinion gear, drive disc and headstock components

It is very important to show how the pore sizes affect the dimension of the pinion gear, drive disc and headstock components. During the design stage of the castings, different allowances like shrinkage allowance, machining allowance, draft allowance, etc. were given for pattern making. After the parts were removed from the sand mold cleaning and fettling processes were done for finishing. Though there is a difference between the required dimensions and the dimensions obtained after the finishing operation has done on the parts. The dimension obtained is a little smaller than the required dimension. Furthermore some amount of material is removed from the surfaces of the defective components for the purpose of avoiding pores, blowholes and cavities by machining and grinding processes. The amount of the material removed from the surface of the finished part is mainly depending on the maximum pore depth (to remove pores). Some cavities were repaired by welding operation but most of the defective surfaces cannot be repaired. The actual dimension (after casting), required dimension (after finishing) and obtained dimension and some of the pore sizes (depths) are given in Table 10. All dimensions are in mm.

Table 10: Some dimensions and pore depths of the pinion gear, drive disc and headstock components

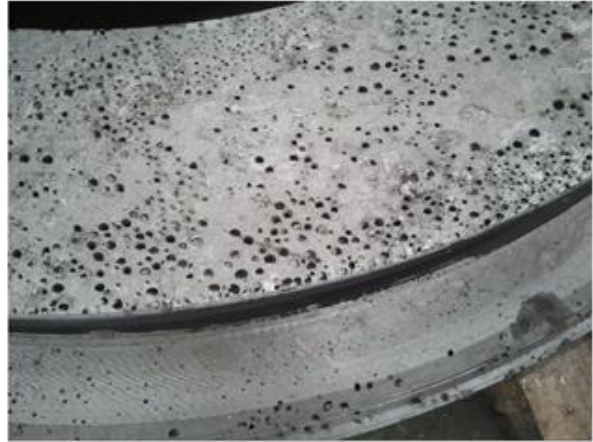
Part	Actual dimension (after casting)	Required dimension (after finishing)	Dimension obtained	pore depths (mm)	Remark
Pinion gear	Ø1397XØ610X720	Ø1391XØ630X700	Ø1390XØ630X698	23,13,10,17,15,12,7,11.5	
Drive disc	Ø1718XØ1528X130	Ø1710XØ1520X120	Ø1708XØ1521X115	24,16,8,18,4,15.5,13.5,9	
Stripe 2	4170X88X28	4160X80X20	4158X80X19	22,17,11,10,9.5,14.5,6,7	Headstock components
Plate 4	612X560X28	600X550X20	601X549X19	21,19,5,12.5,8.5,15,10,9	
Plate 5	Ø441X29	Ø450X20	Ø448X20	22,7.5,15,18,9,14,13,12	
Plate 7	4172X910X27	4160X900X20	4158X898X19	24,14.5,8,11,10,12,9,21	
Plate 8	2349X1682X28	2340X1676X20	2339X1674X20	22,12,13,16,15,14,6,7	
Plate 9	Ø212X28	Ø220X20	Ø221X19	21,17,20,15,12,16,8,7	
Plate 11	608X557X26	600X550X20	598X549X20	21,16,8,4,17,13.5,11,10	

4.6 Photographic analysis

The photographs used for this study are taken by the researcher with the help of digital camera and shown below. It has been seen that the level of porosity on the selected defective components is very serious. Most casting quality problems are originated at the process design stage. Therefore, exploiting defect reduction methods for process design is a wise decision for improving quality of cast products.



(a) Top surface of the defective drive disc



(b) Top surface of the drive disc after first hand grinding



(c) Voids on the top surface



(d) Top surface after final grinding



(e) Bottom surface of the drive disc



(f) Internal wall of the drive disc after first hand grinding



(g) Internal wall after final grinding

Figure 16: Photographs of the defective drive disc sample selected for analysis



(a) Slag inclusion on plate 7



(b) Porosity on the surface of plate 4



(c) Blow holes on plate 5



(d) Blow holes on plate 9

Figure 17: Photographs of the defective headstock samples selected for analysis



(a) Blow holes on internal surface



(b) Repaired shrinkage cavity



(c) Slag inclusions and blow hole



(d) Rough surface finish



(e) Surface crack



(f) Shrinkage cavity and sand sintering



(g) Rough surface finish

Figure 18: Photographs of the defective pinion gear sample selected for analysis

As it has seen from the photographs, the selected components contain different defects. Figure 16 (a) shows the top surface of the defective drive disc component after machining and grinding. In Figure 16 (b), (c), (d) and (e) it has easily identified that both the top and bottom portions of the drive disc are highly affected by porosity. Not only the top and bottom portions, the internal walls of the drive disc also have porosity defect as shown in Figures 16 (f) and (g). The headstock components contain blowholes Figure 17 (c) and (d). The visual inspection of the pinion gear shows in addition to the porosity defect, formation of slag inclusions Figure 18 (c), poor surface finish on the face (b) and rough casting surface on the teeth profile (g), crack on the surface of the gear (e), sand sintering and formation of shrinkage cavity (f). The defect (porosity) which is observed in the pinion gear, drive disc and headstock components is random without pattern. Most of the pores in these castings are spherical and oval in shape.

Defect sources may connect with input materials, technology and skilled man power problems. Surface defects may be improved by various methods. If strength and toughness are critical and cost is not of overriding importance, then castings are often subjected to further processing to improve their properties and qualities. Many of the problems that occur in finished products have their origin in the original casting. Internal defects created during casting can be very costly, since they are usually difficult to detect, and are often not found until later processing stages or even in service. Some defects are caused by simple mistakes, but these are specific to the individual casting process [41].

It is necessary to measure the depths of the pores and determine the level of the quality of the cast. After final grinding of the pinion gear, disc drive and head stock components measurements of diameter and depth of pores were carried out using Vernier caliper. About 100 points, with the major damage was measured in 5 days 20 measurements per day and the results are shown in the table below.

Table 11: Various pore sizes (all dimensions in mm)

Sample	1 st day		2 nd day		3 rd day		4 th day		5 th day	
	Depth	Diameter	Depth	Diameter	Depth	Diameter	Depth	Diameter	Depth	Diameter
1	23	9	17	7	9.5	8	15	9.5	12	6
2	15	7	17	10	12	10.5	22	6	12	8
3	12	7.5	15.5	12	7	7	12.5	7	9	6
4	16	10	10	10	7	5	5	8	19	6
5	11.5	7.5	8	12	6	6.5	5	7	21	8.5
6	15	8	13	10	14.5	8	7.5	5	24	9
7	7	8	7	6.5	7	6	15	8.5	12	9
8	22	7.5	10	8	11	8	18	10	13	7
9	8	6.5	21	9	8.5	6.5	9	6	16	5.5
10	18	9	9	7	12	7	21	6	15	10
11	15.5	8	9.5	7.5	15	6.5	14	7	13	8.5
12	8	8.5	14.5	7	10	5.5	13	9	14	10
13	16	8	7	5	10	6	12	4.5	13	9
14	8	8	6	7	13	7	13	5	6	5.5
15	8	7	15.5	9	9	8	21	8.5	11	7.5
16	4	5.5	17	10	4	5	22	8	13.5	9
17	24	9	19	10	8	8.5	14.5	6	17	9.5
18	13.5	11	12.5	7.5	9	4	8	11	16	9
19	17	8	7	5	10	8	11	9	22	5.5
20	11	6	11	7	17	6	10	7.5	20	9

The pore depths and diameters are graphically represented in Figures 19 and 20 respectively.

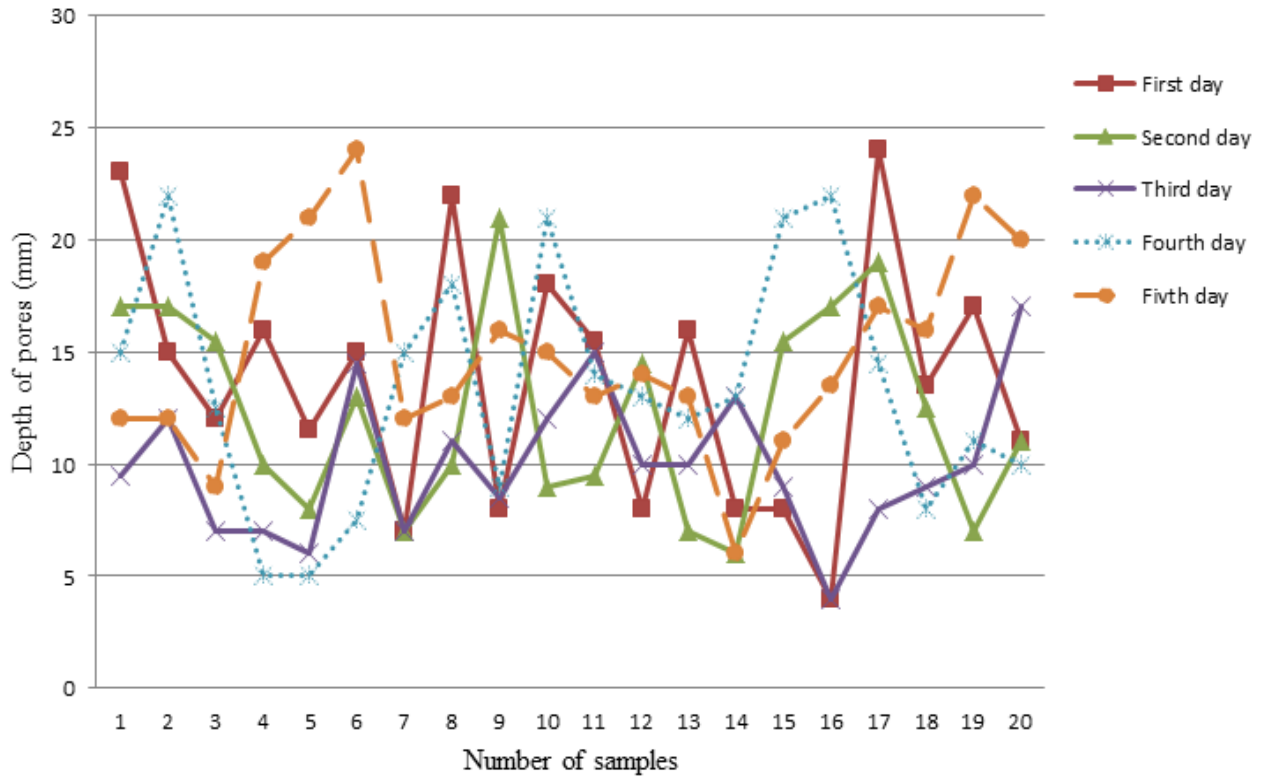


Figure 19: Depth of pores (mm)

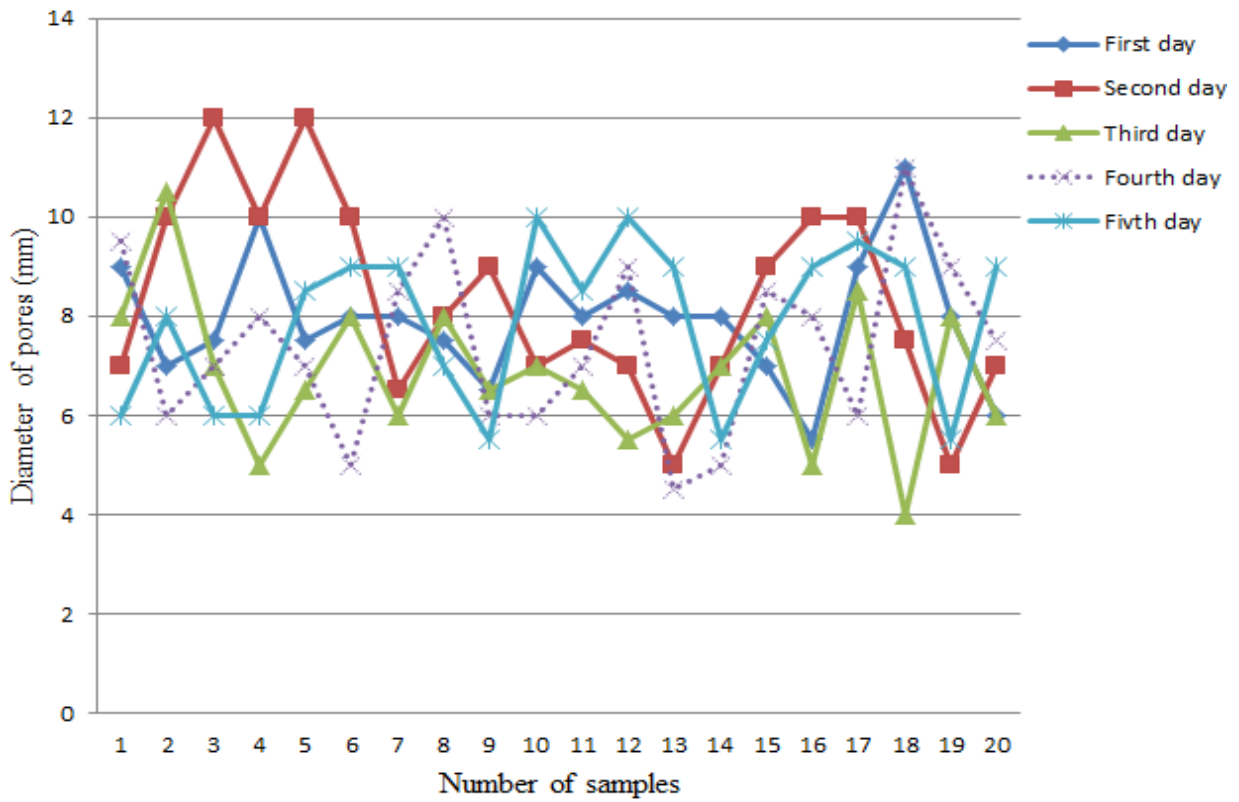


Figure 20: Diameter of pores (mm)

Based on the measurement obtained the maximum depth and diameter of the pores are 24mm and 12mm respectively. These largest values were obtained from the top surface of the drive disc having a plate thickness of 40mm. If 24mm amount of metal is tried to be removed from the surface of the drive disc for the purpose of avoiding the pores from the surface and making the part defect free, the remaining 16mm thickness is out of the desired dimension. This leads to the quality level of the part (drive disc) is to be taken as reject due to unsatisfactory design requirements provided by the customer and the rework cost is very high. This in turn highly reduces the productivity of the AMBI. The maximum bubble diameter (for steel) of entrained air adjusted for a temperature of 1500⁰C and depth of 200 mm are 18.1mm and 17.3mm respectively as indicated in Annex D. But the maximum diameter of 12mm is obtained from the portion of the drive disc having 40mm thickness. Comparing the temperature and depth proportions of the standard value and measurements at AMBI, one can easily understand that the porosity level at AMBI is very severe.

4.7 Construction of the U-Chart

The data in table 12 and 13 are based on the measurements made and given in Table 11. Nonconformities or defects are classified in four classes based on their seriousness as very serious, serious, major and minor. According to ANSI and ASQC the weights given for very serious, serious, major and minor nonconformities are 100, 50, 10 and 1 respectively.

The average number of nonconformities per unit for each category is calculated as follows.

$$\text{For very serious nonconformities } \bar{u}_1 = \frac{22}{9(11)} = 0.222$$

$$\text{Similarly, } \bar{u}_2 = \frac{37}{9(11)} = 0.374$$

$$\bar{u}_3 = \frac{38}{9(11)} = 0.384 \text{ and}$$

$$\bar{u}_4 = \frac{2}{9(11)} = 0.02$$

Using equation (6), the center line (CL) of the U chart is;

$$\bar{U} = 100 (0.222) + 50 (0.374) + 10 (0.384) + 1 (0.02) = 44.76$$

Table 12: Data for Nonconformities in pore depths

Sample	Very serious Nonconformities (c ₁)	Serious Nonconformities (c ₁)	Major Nonconformities (c ₁)	Minor Nonconformities (c ₁)	Total Demerits (D)	Demerits per unit
1	3	6	2	0	620	56.36
2	4	2	4	1	541	49.18
3	1	3	7	0	320	29.09
4	2	3	6	0	410	37.27
5	0	4	7	0	270	24.55
6	2	2	6	1	361	32.81
7	4	6	1	0	710	64.54
8	3	4	4	0	540	49.09
9	3	7	1	0	660	60
Total	22	37	38	2		

The estimated standard deviation ($\hat{\sigma}$) of U, using equation (7) is;

$$\hat{\sigma} = \sqrt{\frac{(100)^2(0.222) + (50)^2(0.374) + (10)^2(0.384) + (1)^2(0.02)}{11}} = 17.04$$

The upper control limit (UCL) and lower control limit (LCL) based on equation (8) and (9) are;

$$UCL = 44.76 + 3 (17.04) = 95.87$$

$$LCL = 44.76 - 3 (17.04) = - 6.36 \rightarrow 0$$

Table 13: Data for Nonconformities in pore diameters

Sample	Very serious Nonconformities (c ₁)	Serious Nonconformities (c ₁)	Major Nonconformities (c ₁)	Minor Nonconformities (c ₁)	Total Demerits (D)	Demerits per unit
1	1	8	1	0	510	46.36
2	2	7	2	0	570	51.81
3	4	5	2	0	670	60.9
4	3	6	2	0	620	56.36
5	0	5	6	0	310	28.18
6	0	6	5	0	350	31.82
7	1	5	5	0	400	36.36
8	1	7	3	0	480	43.64
9	2	6	4	0	540	49.09
Total	14	55	30	0		

The average number of nonconformities per unit for each category is calculated as follows.

For very serious nonconformities $\bar{u}_1 = \frac{14}{9(11)} = 0.141$

Similarly, $\bar{u}_2 = \frac{55}{9(11)} = 0.566$

$\bar{u}_3 = \frac{30}{9(11)} = 0.303$ and

$\bar{u}_4 = \frac{0}{9(11)} = 0$

Using equation (6), the center line (CL) of the U chart is;

$$\bar{U} = 100(0.141) + 50(0.566) + 10(0.303) + 1(0) = 45.43$$

The estimated standard deviation ($\hat{\sigma}$) of U, using equation (7) is;

$$\hat{\sigma} = \sqrt{\frac{(100)^2(0.141) + (50)^2(0.566) + (10)^2(0.303) + (1)^2(0)}{11}} = 16.11$$

The upper control limit (UCL) and lower control limit (LCL) based on equation (8) are;

$$UCL = 45.43 + 3(16.11) = 93.76$$

$$LCL = 45.43 - 3(16.11) = -2.9 \rightarrow 0$$

Based on the above calculations the U- chart for nonconformities in pore depths and diameters are plotted to show the level of porosity defect on the selected defective components. It has seen from Figures 21 and 22 that the process seems in control, but since there are demerits due to nonconformities or defects we need to improve the process to reduce the gap between the control limits and hence reduce the casting defects. So it is very important to determine the causes of defects which made the casting operation out of control and give possible remedies as discussed in the next chapter.

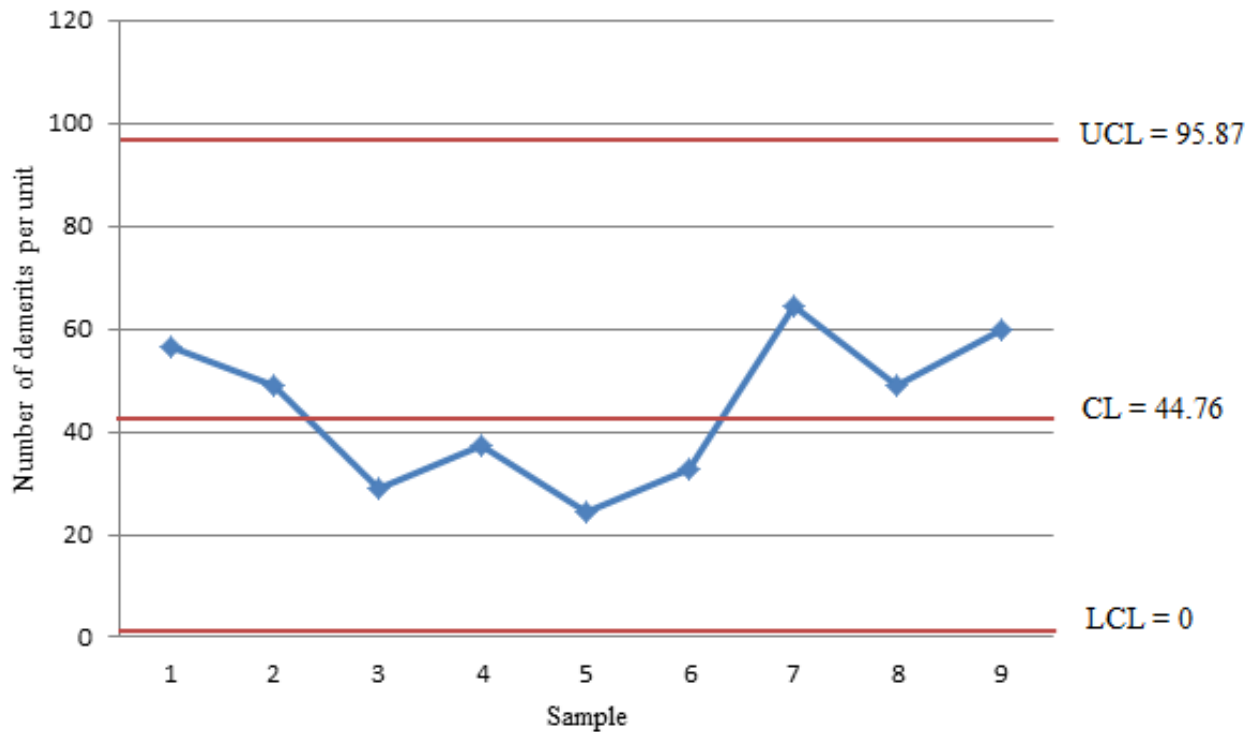


Figure 21: U- chart for nonconformities in pore depths

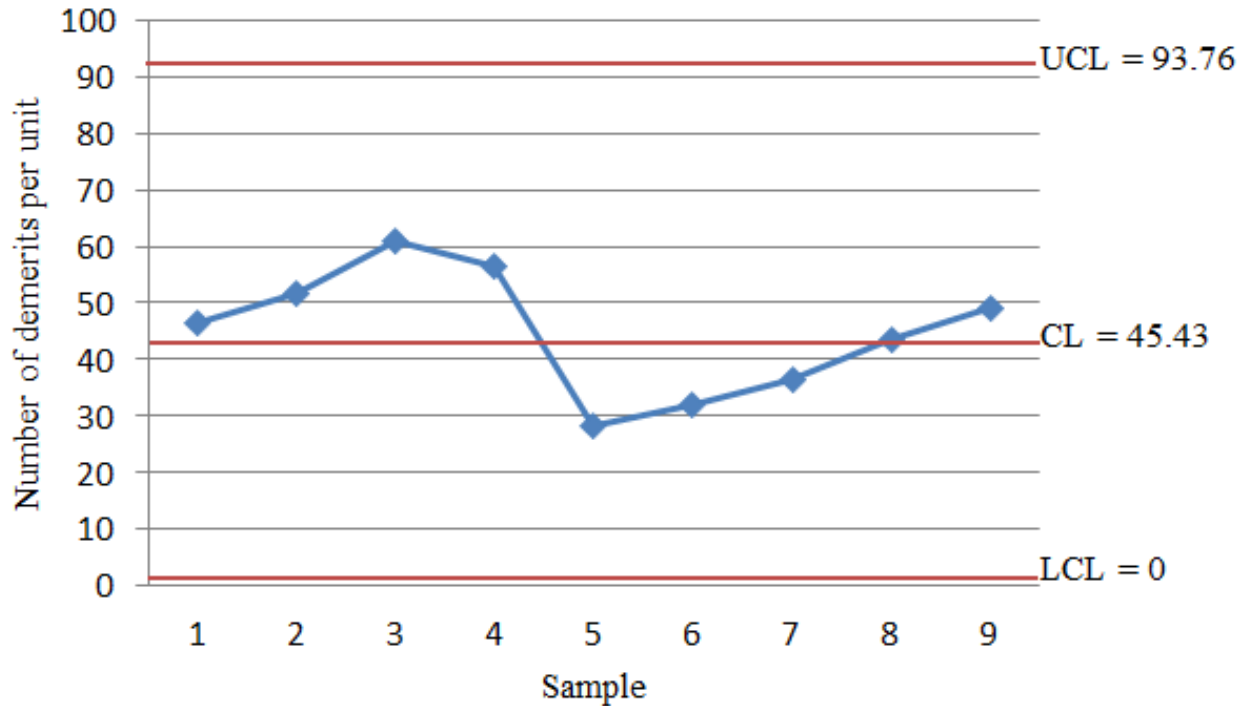


Figure 22: U- chart for nonconformities in pore diameters

4.8 Cost analysis for rework of defective components

High production and rework costs are the main problems observed in the foundry shop of ABMI. It is necessary to analyze the cost that the factory spends for the rework of the defective components.

The gross weights of the pinion gear, drive disc and headstock components are 8698kg, 1637kg and 8251kg respectively. The total gross weight is 18,586kg (8698kg + 1637kg + 8251kg). Remember the metal to sand ratio used at ABMI is 1:5. This means if the weight of the metal to be cast is 100kg we use 500kg of sand for mold preparation. And for the molding we use 1.2% resin (example for 100kg of sand we use 1.2kg resin) and 0.6% catalyst (example for 100kg of sand we use 0.6kg catalyst). The material cost in table 5 is based on this data obtained from the industry.

Table 14: Material cost for rework of the selected defective components

No.	Description	Quantity	Unit cost (Birr)	Total cost (Birr)
1	Metal scrap	18,586kg	10.00	185,860.00
2	Silica sand	92,930kg (60m ³)	8,000.00/10m ³	48,000.00
3	Resin	1115.16kg	84.00	93,673.44
4	Catalyst	557.58kg	68.00	37,915.44
5	Wooden pattern	9 pieces of desired size and shape	size and shape dependent	5407.85
Subtotal				370,856.73

Table 15: Tools and equipment cost

No.	Description	Quantity	Unit cost (Birr)	Total cost (Birr)
1	Medium frequency induction furnace	18,586kg of metal	1785/500kg	66,352.02
2	Cutting disc	50	60	3000
3	Grinding disc	24	40	960
Subtotal				70,312.02

Table 16: Labor cost

No.	Description	Quantity	Working hour	Unit cost (Birr)	Total cost (Birr)
1	Designer	3	72	12	2,592.00
2	Sand preparation	4	16	5.29	338.56
3	Sand laboratory	2	6	5.76	69.12
4	Sand mixing	2	18	5.76	207.36
5	Pattern making	3	36	6.97	752.76
6	Method design	2	36	13.46	969.12
7	Mold preparation	4	4.5	5.76	103.68
8	Charge preparation	2	16	5	160.00

9	Furnace operator	1	54	7	378.00
10	Pouring	2	0.5	7	7.00
11	Finishing	7	53.1	6.25	2,323.15
Subtotal					7,900.75

Table 17: Summary of rework costs

No.	Description	Subtotal (Birr)	Contingency (15%)	Total (Birr)
1	Material cost	370,856.73	55,628.50	426,485.25
2	Tools and equipment cost	70,312.02	10,546.80	80,858.82
3	Labor cost	7,900.75	1,185.15	9,085.90
Subtotal				516,429.97

CHAPTER FIVE: RESULT AND DISCUSSION

In this chapter the results from data analysis and experiments are presented. The results are discussed in terms of their features including photographic analysis and correlated to the conditions imposed in each experimental procedure. First, results from identification of the possible causes and effects (porosity and blowhole defects) on manganese steel castings are presented, followed by the issues concerned with remedies for casting defects during the production procedure of the steel castings.

As shown in the U- charts for pore depths and diameters (Figures 20 and 21), the process needs improvement and hence the task does not end with the identification of an out of control process. In fact, the difficult part begins when out of control process has been found. Determination of the causes for out of control process is very important through knowledge of the process and sensitivity of the output casting quality. This is usually a collective effort, with people from product design, process design, tooling, and production. A cause and effect or Ishikawa diagram is often an appropriate tool here to find out the actual reasons behind the porosity and blowhole defects. Here the special causes have been identified and appropriate remedial actions are provided.

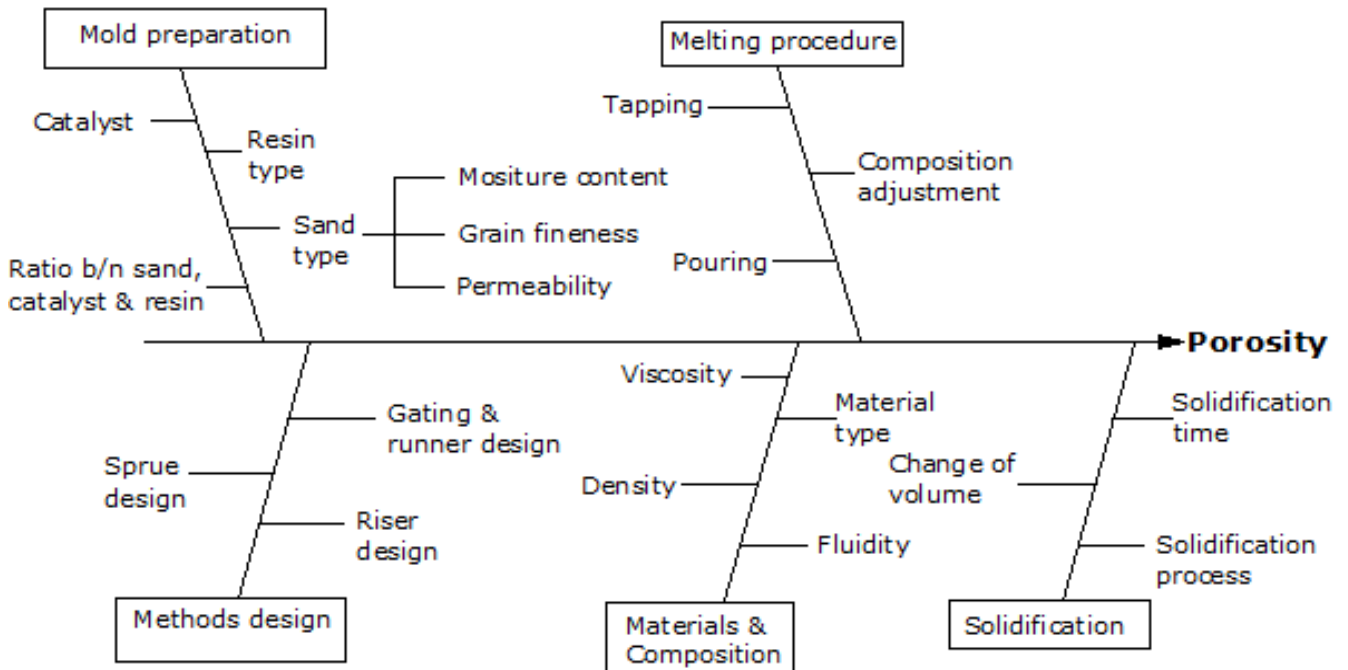


Figure 23: Cause and effect diagram of porosity

Analyzing the causes and effects using fish bone diagram may help to develop remedial actions to reduce steel casting quality problem. Porosity in steel castings is formed due to many reasons as discussed here in under.

Much of the porosity in castings is not the result of excess gas pressure forming blowholes or gas solubility forming pinholes but is the result of oxides unlike the fact expressed in equation (1). In fact, most of the surface or subsurface porosity is likely due to oxide formation. In steel castings, many of the reoxidation inclusions include associated porosity. Frequently when the inclusion material is removed by blasting, the associated porosity remains. Drossy, gassy areas in steel castings are often mislabeled porosity by customers. Reoxidation in steel affects every factor required to form a bubble. The inclusion material floats higher in the casting reducing the pressure to be overcome. The less stable oxides, such as iron or manganese oxide, are reduced by carbon, forming carbon monoxide, a source of gas for bubble formation.

Higher levels of oxygen locally reduce the surface tension that must be overcome to form a bubble. Dross or glassy oxides occur in all cast metals operations. The entrapment of this glassy material or its formation during casting often results in porosity. Control of this porosity is a matter of controlling the formation and entrapment of oxides in casting. Cast iron has sufficient carbon content so that carbon monoxide forms in preference to other oxides at the molten metal surface at normal tapping and pouring temperatures. Because of this, good casting operations are able to clean the surface of the iron prior to pouring. In steel, a continuously forming slag prevents a clean surface. Large porosity in steel castings is often labeled a slag blowhole, with some oxide or dross attached to a large porosity cavity. Fluid slag entrapment or reoxidation have been identified as sources [9].

Although several variables have been identified that either exaggerate or promote the formation of porosity defects in steel castings, these variables are, in one way or another, related to the gaseous decomposition products generated by the resin during casting. Decomposition gases consisting of both H_2 and N_2 are readily liberated during pouring and subsequent solidification. High melting temperatures as $1650^{\circ}C$ in the case of ABMI (based on information obtained from the industry) further enhance both the breakdown rate and amount, as well as favor increased gas solubility in

the liquid metal. High pouring temperatures also have a significant effect on liquid metal surface tension, which has been shown to have a significant role on porosity formation [42].

The same effect of alloying elements on the solubility is well known. If the melt initially has a high gas content resulting from the use of poor charge metallic or carbon additives, then the tolerance for additional solution of nascent mold or core gases is reduced considerably, and porosity formation becomes extremely favorable [43]. As per the standards provided by AFS, the sulfur content for most steels should be 0.035%. But the sulfur contents determined from the spectrometric analysis at AMBI has found as 0.04% for the drive disc and 0.05% for the pinion gear and headstock components. This shows 0.005 and 0.015% increment of the sulfur content on the material of the selected defective components that may lead to formation of defects on steel castings.

As indicated in the literature review permeability (the ease with which gases can pass through the mold), is one of the important properties of mold sands and highly associated with porosity defects. Permeability is determined by measuring the rate of flow of air through a compacted specimen under standard conditions. The test for green permeability is carried out on the AFS standard cylindrical specimen, retained in its ramming tube and found as 150-350 [15]. The equipment to measure permeability of the mold at AMBI is not working properly at the time when this research was conducted. After mold preparation vent holes were created randomly with steel sticks without any measure and reference.

Another standards for molding sands from AFS include moisture content (0.5%), clay content before wash (16-20%) and clay content after wash (1% max). The respective results obtained at AMBI are 0.325%, 15 and 0.25%. Moisture can enter the mold cavity in a number of ways. These may be related to the mold paint and moisture absorbed from the atmosphere by the mold after it has prepared. Moisture may appear also in sand which is going to be used in mold preparation. The test results show that the moisture to be added in the mold cavity from the sand is very little as it is kept below the maximum recommended – 0.5%. Since still the sand contains moisture (in small amount), there can be formation of vapor and steam and reaction with low melting metal products which is considered as one cause of porosity and sand sintering formation. Results show

that there are no chances for defect formation in the selected defective components associated with the clay contents. (The clay content after wash is within range).

It is of great importance to the foundryman to fully understand the nature and fundamental chemistry of no bake binder systems in order to assure their correct usage. Any one of a number of minor operating variables can exert a cumulative effect on the performance of no bake binders. The sand, resin and catalyst ratio at ABMI is always taken as 100:1.2:0.6 for all steel castings. As seen from the foundry practice of ABMI, no careful attention was given for the time spent for proper mixing and distribution of resin binders with the silica sand and catalyst due to outdated mixing equipment. But Naro [31], explains that short mixing cycles of 10 – 40 seconds total time tend to promote the formation of both surface and subsurface porosity. Only trace amount of subsurface porosity probably better described as microporosity are found in castings made with molds mixed for intermediate times of 60 – 80 seconds. Sound castings are obtained when the total times ranged from 2 – 4 minutes.

Grain fineness has also something to do with permeability of a mold which in turn has high role for porosity formation. 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 [44]. Therefore, the GFN values for molding sands shall remain within a certain range to obtain sound castings. The GFN values as per ABMI's practices are made to stay within 40 – 60. The lower (coarser) ranges are used for ferrous and the upper (finer) ranges are used for non – ferrous materials. Gases need to be driven out quickly from molds which are made for pouring steel materials and so such molds should be made from coarser sands. So there should be some correction by combining with coarser new silica sand with the reclaimed one.

If considering the pouring temperature range, the practice in ABMI's foundry shop, where the castings are produced is higher than the standard pouring temperature and this higher temperature may lead to porosity and fuse sand particles, dusts will char, volatile materials evaporated out to the surface and deposited due to this high temperature the softly rammed mold will be dried more than the need and get cracked out. This is because of the absence of temperature regulation as there is no device to control the pouring temperature. The solidification time for steel is not

controlled in a proper way and thus the high temperature liquid metal remains in the mold for long time causing formation of bubbles due to dissolved gases and hence high chance of porosity defect. At the same time the pouring mechanism was manual with lip type ladle, thus the uncontrolled filling of the mold leads to turbulence flow.

The flow characteristics of liquid metal whether Re is greater than the critical (greater than 2000) or not, where Reynolds number (Re) is defined by:

$$Re = \frac{Vd}{\nu} \quad (16)$$

Where V is mean velocity;

d is linear dimension of the mold channel section and

ν is kinematic viscosity of the liquid.

The mean velocity of the molten metal during pouring can be determined from Bernoulli equation

$$V = \sqrt{2gh} = \sqrt{2 * 9.81 * 0.45} = 2.97\text{m/sec}$$

The kinematic viscosity $\nu = \mu / \rho$

Where ν = kinematic viscosity (m^2/s)

μ = absolute or dynamic viscosity (N s/m^2)

ρ = density (kg/m^3)

$$\text{Therefore } \nu = \frac{0.006}{7860} = 7.634 * 10^{-7} \text{m}^2/\text{s}$$

$$\text{Then the Reynolds number } Re = 2.97 * 0.3 / 7.634 * 10^{-7} = 1,556,195.965$$

Turbulent flow is associated with high values of (Re) and therefore with high velocity, large flow channels and low kinematic viscosity. According to Re value the flow may be laminar which does not affect the quality of casting or turbulent, which may lead to the formation of porosity, sand sintering (burn on) or other related surface defects. This number also determines the change in the cross section of a vertical sprue that will compensate for the acceleration of the molten metal as it drops through the sprue under the influence of gravity. The height of pouring and time of pouring have not been properly adjusted. Especially pouring height varied with the wide range and lead to high pressure head that again influence on the flow characteristics of the liquid metal and turbulence flow facilitates liquid metal and mold material reaction.

Flow of liquid metal has characterized in to three main forms stream flow, fragmental flow and drop type flow. Flow characteristics are depending up on viscosity, flow rate, time of pouring, and height of flow, surface tension and density of the liquid metal. In the condition of the pinion gear, drive disc and headstock castings the melting temperature is high the viscosity reduces as a result velocity increases and flow rate also increases [45]. The height of pouring is above 200mm (as per observation), thus the pressure head is high. The conditions lead to turbulent flow of the steel. Obviously in this case the flow character was stream type as the feeding head having large diameter was acted as a pouring cup be the reason for high hydrodynamic force that break the bottom of the mold wall and detach the sand due to its impact. The magnitude of hydrodynamic force which can be calculated by:

$$F_{hd} = 2 \rho \pi r^2 \sqrt{2gH} \sqrt{2g} (\mu^2 H + h) \quad (17)$$

will be greater than 1.62N known as a critical value of hydrodynamic impact force in the flow of ferrous metals including steel in which above this value the flow is turbulent and the cast is fully defective on surface and in subsurface due to porosity formation.

Where, F_{hd} is hydrodynamic force (N);

ρ is density of liquid metal (g/cm^3);

r is radius of the sprue (mm),

μ is viscosity of the liquid metal;

g is acceleration due to gravity (m/s^2);

H is height of the sprue (mm) and

h is pressure head (mm).

The furnaces used for melting of ferrous metals at ABMI are not properly identified. Medium frequency induction furnaces are used for all types of ferrous metals. The only method to differentiate one metal from the other is the melting temperature. Again there is no proper control of the melting temperature in the foundry shop. The reason behind is the pyrometer used for melting temperature measurement is not properly working at the time when this research is conducted. The pyrometer is not giving exact and accurate temperature readings. This improper temperature may lead to porosity and other casting defects. In addition to this there is no control for pouring time. Pouring is done traditionally by old ladles. Use of proper furnace types for different steel materials, provision of temperature controlling devices for melting and pouring

practices, proper gating system design, coating proper refractory materials may improve the condition of porosity and other defects on steel castings of various categories at ABMI.

Skilled man power problem, equipment problem, gating technology problem, material related problem, methods utilized and metal property are the major factors for the defects formed at ABMI. The foundry shop at ABMI lacks skilled man power; most of the activities have carried out traditionally. The technical facilities are limited to old flasks, improperly rammed ladles were used. Thus complicate the pouring and melting process, which consequently cause the raise of porosity and other defects.

Amount of material removed from the surface of the defective components

As explained in chapters 2 and 4, there are different allowances given for the pattern in order to obtain the desired size and shape of the final castings. However ABMI is suffering from size related problems. There are surface and subsurface defects even after the final stages of casting. Some attempts have been done to repair the defective components. As an example shrinkage cavities on the pinion gear are filled by welding process. Although some of the defects cannot be repaired due to severe level of porosity. The only solution assumed at the industry to avoid such non repairable defects (pores and cavities) is removing the pores and cavities by machining and grinding operations. Consequently there is size reduction of parts below the desired dimensions specified by customers. Therefore the amount of material removed from the surface of the defective components is basically depending on the maximum depth of pores. The required dimensions by the customer after finishing, actual results obtained and maximum pore depths on the selected defective components are provided in the Table 18.

The 23mm maximum pore depth has found on the internal diameter ($\text{Ø}630\text{mm}$) of the pinion gear. Removing this pore results the final internal diameter of the pinion gear to increase to a value of $\text{Ø}653\text{mm}$ which is much lower than the required. Similarly the required thickness of the bottom portion of the drive disc in the design was 45mm, as indicated in Figure 11. However due to porosity defects the dimension obtained is going to be 16mm. This amount of large variation of dimension is because of the 24mm depth of pore and actions to be taken to avoid the pores by machining and grinding operations. So there is high chance for the component quality level to be

taken as a reject due to unsatisfactory design requirements and the rework cost is very high as shown in the cost analysis.

Table 18: Maximum pore depths on the selected defective components

No.	Dimension of components	Required dimension (after finishing),mm	Result (mm)	Maximum pore depth (mm)	Variation in dimension (mm)
1	Pinion gear	Ø1391XØ630X700	Ø1390XØ630X698	23	653
2	Drive disc	Ø1710XØ1520X120	Ø1708XØ1521X115	24	91
3	Stripe 2	4160X80X20	4158X80X19	22	58
4	Plate 4	600X550X20	601X549X19	22	527
5	Plate 5	Ø450X?X20	Ø448X707X20	21	686
6	Plate 7	4160X900X20	4158X898X19	24	874
7	Plate 8	2340X1676X20	2339X1674X20	22	1652
8	Plate 9	Ø220X?X20	Ø221X450X19	21	429
9	Plate 11	600X550X20	598X549X20	21	528

The maximum pore depth on the headstock components varies from 21 to 24mm. But the quality level of these headstock components is taken as acceptable while these much pore depths are there in the components. As discussed in chapter 4, the application of the headstock is to carry very huge components like rollers gears of various sizes in horizontal position so it is subjected to very high compressive loads. Existence of porosity defects on the headstock components degrades the mechanical properties; specifically the strength and causes failure of the part without giving the desired service life.

Other casting defects on the selected defective components

In this research porosity, blowholes, surface cracks, sand sintering due to the formation of shrinkage cavity and rough surface finishes are the defects obtained in the pinion gear, drive disc and headstock components. It has seen that any attempt to avoid these defects from the components may highly reduce the desired dimension and lead to the quality level of the parts to be taken as a reject. On the other hand as explained in the problem statement assembling the

defective components or taking the quality level of the defective components as acceptable result in short service life or failure of the parts to give the desired service.

The photographs in Figures 15, 16 and 17 show that porosity, blowhole, micro crack and sand sintering have strongly affect the surface finish of the pinion gear, drive disc and head stock components produced. The procedure of porosity, blowhole, micro crack and sand sintering removal also needs various consecutive steps, which mainly include grinding and machining. The process requires time, tools, metal loss and labor as a result of which huge finance is required. As it has been discussed in the previous chapter the pinion gear, drive disc and headstock components are produced from manganese steel. At this point analyzing the formation of porosity, blowhole, crack, sand sintering and rough surface finish in terms of steel properties is necessary. From observation, practical experience of the industry and brain storming of operators, it has been found that in the foundry shop, where the pinion gear, drive disc and headstock components are produced temperature control of melting has not been done properly. Because of this the melting temperature in most cases reach up to 1800 °C, which is above the normal range that ultimately led to porosity formation and sand expansion as a result of which sand sintering, has been formed on the surface of the cast. It has been understood that dry silica sand with hand ramming technique has been used for molding. Hand ramming causes soft mold as a result of which mold erosion occurs as one factor for sand sintering.

Knowledge about fluid flow during the filling of castings is important not only in itself, but because it affects heat transfer both during and after filling. It is because of this reason that more sintered sand remains on the surface of the cast at low temperature, while solidification takes place or porosity and sand sintering starts to form at high temperatures. The gating system used in the foundry shop of ABMI for pouring the molten steel was pressurized top, bottom and side gating system which may be the reason for turbulent flow. Top gating system is also mostly suspected for air entrapment and hence led to formation of bubbles and as a result porosity defects.

From the observation and brainstorming of employees it has been understood that the riser type is a cylindrical in shape and the correct shape fitted with the mass and geometry of the cast has not clearly identified for different cast sizes and shapes. From data analysis it has been seen that the

size of the riser which was not match with the 4784kg mass of pinion gear cause excess metal loss. The total mass of the waste metal from one pinion gear casting is 3914.18Kg. This amount of metal is also affected by porosity, blowhole and sand sintering and affects the remelting process causing large amount of dross and slag. Manual ramming was also used on molding process. Other technological and human factors such as skill and knowledge gap among employees, temperature controlling problem, molding techniques are also considered as reasons of porosity, blowhole, crack and sand adhering on the pinion gear, drive disc and headstock internal and external surfaces.

To avoid porosity in steel castings, hydrogen contents in casting should remain under 0.0006%. Porosity occurs in the range of 0.0009 to 0.0013% with porosity always present at levels in excess of 0.0013%. Hydrogen is picked up in melting. Hydrogen problems in steel casting production are most problematic in alloys especially low temperature or high strength grades. Hydrogen is responsible for loss of ductility in tensile tests and can be reduced by low temperature baking. Hydrogen is thought to be responsible for wormhole like porosity that originates at the surface and extends toward the thermal center of the casting. The occurrence of hydrogen related problems also seems to be dependent on relative humidity and therefore more common in more temperate regions.

Pinholes can also form from nitrogen in steel casting so the nitrogen contents should remain under 0.0012%. The oxygen blow in melting practices reduces the hydrogen and nitrogen contents of the steel. Nitrogen levels are elevated by reheating in melting after deoxidation. The use of nitride formers such as zirconium or titanium is often used to avoid problems with nitrogen. They should be added after primary deoxidation to prevent the oxidation of these nitride formers. Control of nitrogen requires minimizing the nitrogen in the melt charge, maintaining at least 0.30% silicon in the charge, a carbon boil of at least 0.30%, using lower voltage settings later in the heat, and minimizing exposure through compact streams and rapid tapping. Higher moisture contents in molding sands and higher relative humidity gives more pinholes [9].

As discussed previously porosity is not the only defect on the pinion gear, drive disc and head stock components of manganese steel at ABMI. Surface crack, sand sintering due to formation of shrinkage cavity and rough surface finish are also the main problems associated with steel

castings. Under practical conditions castings, like all metallurgical products, contain voids, inclusions and other related defects or flaw, which cause quality variation. Flaw may make the normal function or appearance of the product to be in poor condition and may lead to the possibility of salvage or, to rejection as well as replacement [18]. Many authors agreed that decision about level of casting defects is dependent upon the defect itself and its significance in relation to the service function of the casting and to the quality and inspection standards being applied in the particular industry or nation. Defects may be originated from the casting design, the technique of manufacture and the application of manufacturing technique as well as the materials to be cast. A defect may arise from one source or from a combination of factors based on, which the necessary preventive mechanism has to be devised. From the above it is clear that defects can be minimized by a clear understanding and identification of their fundamental causes.

The type of sand used for mold making was silica sand bonded with furan resin. Moreover it was repeatedly used and reclaimed, where possibly iron oxide that is plastic in nature and piled up at higher temperature due to its low refractoriness was included and reduced the quality of silica sand in that when it is pure its fusing temperature is high as a result of which mold material erosion is reduced. More over the iron oxide may be reduced to iron and cause fusing and sticking. The temperature control mechanism used was worked poorly, as a result of which the melting temperature of the manganese steel reached up to 1650°C (as informed from the operator of the furnace). In contrary the refractoriness of silica sand reaches maximum up to 1580°C (as per the standards of AFS) and starts to collapse above this temperature. In this regard the silica sand was fused and reacted with liquid metal resulting in burn on. Due to the higher temperature the binder was evaporated at earlier time and form steam that reacted with the liquid metal at the same time molding sand was eroded and the detached sand particles penetrated the metal mixed within the molten metal distributing into many parts of the steel cast.

Pouring was carried out using the old ladles, where small refractory particles detached from the mold wall and coating clay can be poured with the liquid metal and increase the formation of drosses and reacting with liquid metal that causes the formation of sand sintering.

Another problem with the steel casting quality found was rough surface finish. The temperature of pouring is very vital for the surface finish of the castings. High pouring temperature causes poor

surface finish [45]. Moreover the silica (SiO_2) content plays a vital role in getting good surface finish. For low carbon steel the silica content should not be less 98%. Regarding temperature of the sand the hot sand causes rough surface problem. The temperature of the process sand should not be more than 45°C . Finer sands give good surface finish and coarser sands give rough surface. The hot sand causes rough surface problem. The temperature of the process sands should not be more than 45°C .

Practice shows that when the molten metal enters the gaps between the sand grains, the result would be a rough casting surface. This can also be caused by higher pouring temperatures. Choosing, appropriate grain size, together with a proper mold wash should be able to eliminate this defect. The ideal mold would possess a smooth, impermeable surface capable of being reproduced on the casting of both ferrous and non-ferrous metals. At higher temperatures surface roughness and sand adhesion can be encountered, with loss of appearance and increased dressing costs. In some case the molding material becomes infused with metal to form a solid mass, which may be difficult to remove especially if the condition occurs in a confined pocket the casting itself may be scrapped.

Finer sands give good surface finish and coarser sands give rough surface. Many authors in the work (www.keytometals.com) agreed that compactness of the mold is very important for getting good surface finish of the casting [46]. High mold hardness gives good surface finish of the castings. On the other hand low hardness gives poor surface and swelled mold. Roy [46] recommended that the position of the ingate plays a vital role for the surface finish of the castings. For steel castings, ingate located at the bottom of the casting gives good surface finish.

CHAPTER SIX: CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH AREA

6.1 Conclusions

- Porosity is one of the main defects in steel castings, which requires clear understanding of its causes and developing the remedial method by analyzing the defect is very important. Physical observation, photographic analysis, cause and effect analysis, control charts, measurement of depth and diameter of pores of the selected cast manganese steel components confirmed that the pinion gear, drive disc and the headstock components are under dimension due to porosity and the defect level is very severe that the products will not give the desired service.
- The paper clearly shows the means of finding the causes of the defects during the production stage of manganese steel castings and the way of taking possible remedies for steel casting quality problems. From the experimental analysis in chapter 4, mold preparation, molding material property, pouring temperature and time, poor gating system design, inappropriate material selection and proper utilization of reclaimed sand are the main causes for the defects.
- The required bottom plate thickness of the drive disc in the design was 40mm; however due to the porosity defect the dimension obtained is 16mm. This amount of large variation of dimension is because of the 24mm pore depth and actions taken to avoid the pores by machining and grinding operations. Similarly, maximum pore depths on the pinion gear and headstock components are found as 23mm and 24mm respectively. Removing these amounts of materials from the finished surfaces highly reduces the desired dimensions of the parts. So there is high chance for the components quality level to be taken as a reject due to unsatisfactory design requirements and the rework cost is very high; 516,429.97 birr.
- Finally, inadequate mixing that result in poor distribution of the binder components which accentuate porosity formation must be improved. Better combinations of the process parameters like sand binder ratio, mold permeability, GFN, pouring temperature and deoxidant amount are the leading parameters for optimizing the process in order to reduce the casting defects.

6.2 Recommendations

- The industry should have a research center that follow different casting defects which occur in the production system and give the possible remedies.
- The industry should have to improve the current documentation system, especially in the area of casting process parameters like melting temperature, pouring time and rate and other parameters used for production process so that it helps for further improved researches.
- Some machines and equipment of the industry are too old and almost obsolete, and the management of the industry is better to think about it.
- The industry's laboratory is equipped with few types of equipment and only some of available equipment are functional but few are not working. So the necessary tests are done with the aid of the equipment for small number of characteristics of the sand used in the foundry shop.
- As the quality characteristics of cast products are very large in number and the casting methods are changing with technology, the industry is better to update itself.
- Other researchers can use this study as input for analyzing research procedure to identify the root cause of steel casting defects discussed and other defects which are not included in this research.
- Furthermore, the ideas in this study can be inferred to other Ethiopian metal processing industries using the procedures being developed to reduce problems associated with steel casting quality problems.

6.3 Future research area

After conducting the study and analyzing the different aspects of steel casting quality related problems, the causes and remedies for steel casting defects were provided in this research.

A foundryman is always under tremendous pressure to produce excellent castings within a tight schedule and budget. Traditional approach rarely allows the foundryman to participate in the design and engineering phases prior to the costly production stage.

Process Simulation by Computer Aided Technologies provides valuable information that facilitates participation by the foundry engineer early in the product development stage.

Furthermore a cast part quality is influenced by properties like pouring temperature, fluid life, solidification, shrinkage, slag/ dross formation tendency which are highly reduced with the aid of computer simulations in casting. Research areas related to computer simulations are recommended to be undertaken in the future. This will be very helpful in minimization of casting defects through optimum adjustment of process parameters.

Need for Computer Simulation

- Easy and inexpensive changes during part design;
- To achieve high quality defect-free castings;
- Provide prior knowledge of possible repercussion due to change in design/process parameters;
- Predict the properties of cast products and
- Predict the possibility and nature of defects like misrun, cold shot, hot spots etc.

Advanced casting simulation tools allow the foundry engineer to quickly bridge the gap between design and manufacturing. Optimization or improved efficiency during the manufacturing cycle leads to substantial time and cost savings. Productivity, quality improvements are possible by meticulous usage of simulation procedure.

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ANNEXES

Annex A: Pattern allowances [8].

Annex A-1: Typical pattern shrinkage allowances for various casting materials

Type of metal	Allowance	Approximate shrinkage (%)	Shrinkage allowance (mm/m)
Steel	1 in 64	1.6	15/7
Grey cast irons	1 in 100	1	8/4
Ductile cast irons	1 in 120	0.8	7/8
Aluminum	1 in 77	1.3	13/1
Brasses	1 in 70	1.4	14/4

Annex A-2: Standards of general machining allowance

Type of metal and alloys	Machining allowance (mm)
Cast irons (i) Large size castings (>1000 mm) (ii) Medium size castings (<150 mm)	10.0 3.0
Cast steels (i) Large size castings (>1000 mm) (ii) Medium size castings (<150 mm)	12.0 4.3
Non-ferrous materials (i) Large size castings (>1000 mm) (ii) Medium size castings (<150 mm)	5.0 1.5

Annex A-3: Approximate taper/draft allowances used in sand casting

Height of pattern (mm)	Manual drawn	Machine drawn
Up to 20	3°	3°
20 to 50	1° 30'	1° 30'
100 to 200	0° 45'	0° 45'

Annex B: Average grain size based on grain fineness number [14].

AFS grain fineness no.	35	40	45	50	55	60	65	70	80	90
Average grain size (µm)	390	340	300	280	240	220	210	195	170	150

Annex C: Comparison of properties of no-bake binder systems [33].

Parameter	Process ^(a)							
	Acid catalyzed		Ester cured		Oil urethane	Phenolic urethane	Polyoliso - cyanate	Alumina phosphate
	Furan	Phenolic	Alkaline/phenolic	Silicate				
Relative tensile strength	H	M	L	M	H	M	M	M
Rate of gas evolution	L	M	L	L	M	H	H	L
Thermal plasticity	L	M	M	H	L	L	L	L
Ease of shakeout	G	F	G	P	P	G	E	G
Humidity resistance	F	F	E	P	G	G	G	P
Strip time, min ^(b)	3-45	2-45	3-60	5-60	2-180	1-40	2-20	30-60
Optimum (sand) temperature, °C	27	27	27	24	32	27	27	32
Clay and fines resistance	P	P	P	F	F	P	P	F
Flowability	G	F	F	F	F	G	G	F
Pouring smoke	M	M	L	N	H	M	M	N
Erosion resistance	E	E	E	G	F	G	P ^(e)	G
Metals not recommended	^(c)	^(d)	^(e)	...

(a) H, high; M, medium; L, low N; none; E, excellent; G, good; F, fair; P, poor.

(b) Rapid strip times required special mixing equipment.

(c) Use minimum N₂ levels for steel.

(d) Iron oxide required for steel.

(e) Use with nonferrous metals

Annex D: Bubble size of entrained air adjusted for depth and temperature [9].

Annex D-1: Bubble size of entrained air adjusted for depth of 200 mm

Original	Density (kg/m ³)	Pressure (atm)	Volume (ml)	Diameter (mm)
Steel	7800	1.15	2.70	17.3
Cast Iron	7200	1.14	2.19	16.1
Aluminum	2800	1.05	1.46	14.1
Brass or Bronze	8800	1.17	2.02	15.7

Annex D-2: Bubble size of entrained air adjusted for temperature

Bubble	Temperature (C°)	Volume (ml)	Diameter (mm)
Original	25	0.52	10.0
Steel	1500	3.11	18.1
Cast Iron	1150	2.50	16.8
Aluminum	600	1.53	14.3
Brass or Bronze	1050	2.36	16.5

Annex E: Thermo-physical properties of steel and heat transfer coefficients [25].

Property	Value	Unit
Density	7100	kg/m ³
Viscosity (Dynamic)	0.006	kg/ms
Electrical conductivity	7.14*10 ⁵	Ω ⁻¹ m ⁻¹
Solidus temperature	1475	°C
Liquidus temperature	1525	°C
Thermal conductivity	46.4	W/m ²
Specific heat	628	J/kg ⁰ C
Latent heat of fusion	268	kJ/kg
Heat transfer coefficient at wall (mold metal interface)	1460	W/m ² k