

MANUFACTURING TECHNOLOGY

VOLUME-1

3

THIRD
EDITION

FOUNDRY, FORMING AND WELDING



P N RAO



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Preface

The first two editions of this book have been well received by the teachers and students of engineering colleges. This proves the paradigm adopted by the author in developing this book as totally different from the other books in this area. Since the publication of the second edition, a number of suggestions have been received by the author about the improvements that could be done to the book. Many of the suggestions have been incorporated into this edition, which are explained below.

Many people felt that there were too many chapters in the book, and as a result of this division, there was a certain repetition experienced. Though there is some truth in this, the original intention was to make each chapter for a specific topic, which is convenient from the teaching point of view. However, since there is a need to conserve space, I have reorganised the original 29 chapters into 12 chapters and in the process the repetition experienced has been completely eliminated.

The modifications carried out in the chapters are the following:

- Many illustrations have been redrawn to improve clarity and ease of understanding by the students.
- Topics on tensile testing details, aluminium alloy properties table, laser heat treatment, rapid prototyping, simplified risering design, expanded furnace types, inoculation, degassing, ladles, permanent mould casting, vacuum die casting, low-pressure die casting and squeeze casting have been added.
- Brazing revised fully.

Chapter 1 introduces the different manufacturing processes and breakeven analysis. Chapter 2 discusses engineering materials, laying emphasis on ferrous and non-ferrous materials along with the heat treatment of metals. Chapter 3 is on metal-casting processes. Chapter 4 deals with gating systems for casting, and Chapter 5 is on melting and casting quality.

Chapters 6 and 7 discuss the special casting processes and metal-forming processes respectively. Chapter 8 is on sheet metal operations. Chapters 9 and 10 deal with welding processes. Two new chapters have been added after a careful examination of the syllabi of major universities. They are Chapter 11 on Powder Metallurgy and Chapter 12 on Plastic Processing. With this addition, the syllabi of major universities are fully covered and it is hoped that the book finds universal patronage as in the previous editions.

The website of this book can be accessed at <http://www.mhhe.com/rao/mtffw3e> and contains the Solution Manual and PowerPoint Lecture Slides for Instructors, and Interactive MCQs, chapterwise additional questions and Model Question Papers for students.

I wish to express my sincere thanks to my current employer, University of Northern Iowa, Cedar Falls, Iowa, USA, for providing an excellent environment and facilities which I could make use of in carrying out this stupendous task. I would also like to thank the following reviewers who took time out to review the book.

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It is a pleasure to work with the editorial staff at Tata McGraw-Hill India who made sure that the production comes with the highest quality in the shortest time to ensure the timely availability of the text.

As usual, I would welcome further suggestions regarding the coverage in the book, and would be happy to incorporate the suggested improvements in future editions to make the book more suitable to the changing curriculum needs of the teaching of manufacturing technology.

P N RAO

Visual Walkthrough

CHAPTER OBJECTIVES

Provides a quick look into the concepts that will be learned by the user.

2 Engineering Materials

Objectives

After completing the chapter the reader will be able to

- ▶ Understand the importance of the properties of engineering materials such as strength, hardness, ductility, and toughness
- ▶ Learn about the fundamentals of structure of engineering materials and how they control their properties
- ▶ Get the various details of the plain carbon steels and the variables that control their properties
- ▶ Understand the importance of different alloying elements in promoting the properties in alloy steels
- ▶ Learn different non-ferrous materials from the engineering standpoint
- ▶ Understand the heat-treatment process and learn about the various heat-treatment methods and their application

3.1 INTRODUCTION

Casting is one of the earliest metal-shaping methods known to human beings. It generally means pouring molten metal into a refractory mould with a cavity of the shape to be made, and allowing it to solidify. When solidified, the desired metal object is taken out from the refractory mould either by breaking the mould or by taking the mould apart. The solidified object is called casting. This process is also called founding.

3.1.1 History of Casting Process

The casting process was probably discovered around c 3500 BC in Mesopotamia. In many parts of the world during that period, copper axes and other flat objects were turned out in open moulds made of stone or baked clay. These moulds were essentially in single piece. But in later periods, when round objects were required to be made, such moulds were split into two or more parts to facilitate the withdrawal of the round objects.

The Bronze age (c 2000 BC) brought far more refinement into the casting process. For the first time perhaps, a core for making hollow pockets in the objects was invented. These cores were made of baked clay. Also, the *cire perdue* or lost wax process was extensively used for making ornaments and fine work.

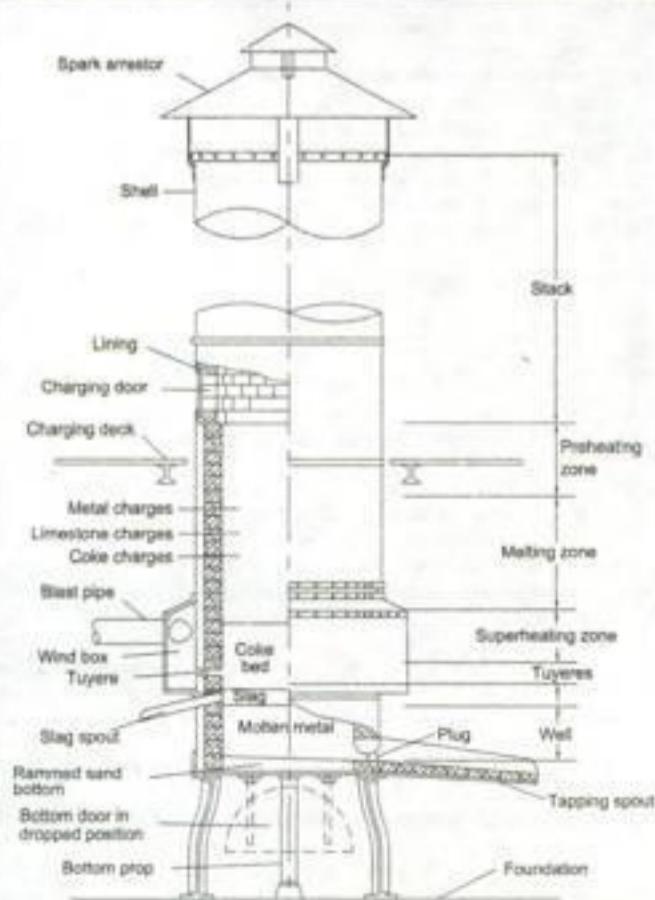
The casting technology has been greatly improved by the Chinese from around 1500 BC. Before that, there is no evidence of any casting activity found in China. They do not appear to have been greatly familiar with the *cire perdue* process nor used it extensively but instead specialized in multi-piece moulds for making highly intricate jobs. They spent a lot of time in perfecting the mould to the last detail so that hardly any finishing work was required on the casting made from the moulds. They probably made piece moulds

HISTORICAL PERSPECTIVE

Provides a brief perspective of historical developments related to the processes discussed.

WELL-LABELLED ILLUSTRATIONS

Provides a complete description of the object in question labeling the various parts to understand the function.



Example 4.4 Calculate the gating requirements for the casting shown in Fig. 4.21 to be cast in C30 steel.

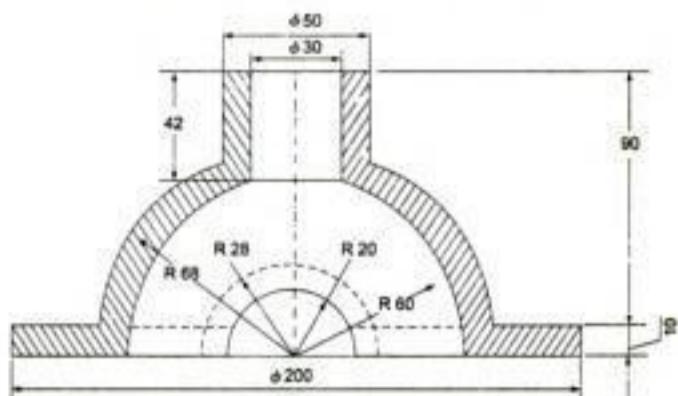


Fig. 4.21

Calculate the volume of the casting as a sum of hemisphere, cylinder and flange volumes:

SOLVED PROBLEMS

Solved problems help the readers review their understanding of the concepts discussed in the chapter.

SUMMARY

Provides the essence of the subject matter covered in the chapter.

Summary

Sand casting is not suitable for applications where large volumes of parts are to be produced or complex geometries are involved. For this purpose, a number of special casting methods are devised.

- Shell moulding is a special casting process used for specific applications that require higher quality castings with thin surface details. It uses resin-coated sand for making the mould that is strong and porous.
- Precision-investment casting utilizes an expendable pattern to create really complex objects without any parting line. This ensures very high precision and excellent properties.
- Permanent-mould casting utilizes a metallic mould to prepare the casting. This helps in lowering costs for mass production, at the same time ensuring a fine-grained structure with improved mechanical properties for the casting.
- Pressure die casting can be utilized for very complex shapes. This process uses a metallic die and the molten metal is injected at very high pressure ensuring the filling of very small cavities at a fast rate. The resulting casting is completely filled with smooth finish and fine-grained structure. It is very economical when produced in large volumes.
- Vacuum diecasting ensures the removal of entrapped air in the die inside the casting, thereby ensuring a sound casting.
- In centrifugal casting, the mould is rotated at high speed, which ensures that the slag and impurities in the molten metal are separated and removed effectively. This ensures that casting produced is sound. There are other variations in this process to cater to the different type of casting sizes and geometries produced.
- Continuous casting allows for the fast production of constant cross-section shapes in large volume.

Questions

- 4.1 What are the various elements that comprise of the gating system?
- 4.2 Describe the objectives of gating systems in any casting.
- 4.3 What are the functions served by the pouring basin in a sand casting?
- 4.4 Give the sketch of a design of a pouring basin with an arrangement for trapping slag.
- 4.5 Explain why the sprue should be tapered.
- 4.6 What are the various methods available to a casting designer to reduce the momentum of the molten metal?
- 4.7 How can slag be trapped in a runner?

Problems

- 9.1 In a given arc-welding operation, the power source is at 20 V and current is at 300 A. If the electrode travel speed is 6 mm/s, calculate the cross-sectional area of the joint. The heat transfer efficiency is 0.80 and melting efficiency is 0.30. Heat required to melt the steel is 10 J/mm^3 .
- 9.2 In a resistance welding of a lap joint of two mild steel sheets of 1.5-mm thickness, a current of 10 000 A is passed for a period of 0.1 second. The effective resistance of the joint is 120 micro ohms. The density of steel is 0.00786 g/mm^3 and heat required to melt is 1381 J/g . The joint can be considered as a cylinder of 5-mm diameter and 2.25-mm height. Calculate the percentage of heat distributed to the surroundings.
- 9.3 A projection welding of 3 spots is obtained with a current of 35 000 A for a period of 0.01 second. The effective resistance of the joint is 120 micro ohms. If the joint can be considered as a cylinder of 6-mm diameter and 2.5-mm height, calculate the heat distributed to the surroundings.
- 9.4 The arc-welding of 6-mm steel plates in butt welding is being carried out at a welding speed of 9 mm/s. The welding transformer is set at 25 V and the current flowing is 300 A. Taking the arc efficiency as 0.85, calculate the temperature to which the plates should be preheated such that the critical cooling rate is kept below 6°C/s at a temperature of 550°C for satisfactory metallurgical quality.
- 9.5 Determine the appropriate welding speed to be used to weld 8-mm C30 steel plates when the power source is at 30 V and current at 325 A. The arc efficiency is 0.80 while the maximum cooling rate allowed is 6°C/s at a temperature of 550°C . The possible welding speeds are 6, 7, 8 and 9 mm/s.

REVISION QUESTIONS AND PRACTICE PROBLEMS

Helps readers test their knowledge gained by reading the chapter and provide hands-on practice in solving problems related to real-life situations.

1

Introduction

Objectives

After completing the chapter the reader will be able to

- ▶ Understand the importance of manufacturing for the mankind
- ▶ Know the different types of manufacturing processes
- ▶ Evaluate the feasibility of a particular process by carrying out the break-even analysis

1.1

MANUFACTURING PROCESSES

The benefits of civilisation which we enjoy today are essentially due to the improved quality of products available to us. The improvement in the quality of goods can be achieved with proper design that takes into consideration the functional requirement as well as its manufacturing aspects. The design process that would take proper care of the manufacturing process as well would be the ideal one. This would ensure a better product being made available at an economical cost.

Manufacturing is involved in turning raw materials to finished products to be used for some purpose. In the present age there have been increasing demands on the product performance by way of desirable exotic properties such as resistance to high temperatures, higher operating speeds and extra loads. These in turn would require a variety of new materials and its associated processing. Also, exacting working conditions that are desired in the modern industrial operations make large demands on the manufacturing industry.

Further, the economics of the manufacturing operation is a very important consideration. To be viable in the modern environment, a product has to be competitively priced besides having the functional and aesthetic appeal. Therefore, it is necessary for the engineer to give a proper thought to various aspects of manufacturing.

Manufacturing processes is a very fundamental subject since it is of interest not only to mechanical engineers but also to those from practically every discipline of engineering. It is so because engineering as a whole is meant for providing various materials for human consumption. For various products such as plant machinery required for chemical, civil, electrical, electronic, textile, etc., the manufacturing process forms a vital ingredient.

A detailed understanding of the manufacturing processes is thus essential for every engineer. This helps him appreciate the capabilities, advantages and also the limitations of the various manufacturing processes. This in turn helps in the proper design of any product required for him. Firstly, he would be able to assess the feasibility of manufacturing from his designs. He may also find out that there are more than one process available for manufacturing a particular product and so he can make a proper choice of the process which would require the lowest manufacturing cost and would deliver the product of desired quality. He may also modify his design slightly to suit the particular manufacturing process he chooses.

Manufacturing is defined by the Merriam Webster online dictionary as *to make into a product suitable to use*. Manufacturing remained as a craft till the first industrial revolution towards the end of the 18th century with low volumes and single-piece productions. It required highly skilled craftsmen to individually produce the pieces and fit them when the assembly was required. This was a slow and expensive process, but in the absence of any machines, that was the only thing that was possible. The availability of the steam engine and coal-fire furnaces made the invention of a number of steam-power driven machinery to greatly increase the manufacturing capacity. A large number of inventions related to machine tools took place during this period and continued into the 19th century. Towards the end of the 19th century with the invention of electricity and better engineering materials, manufacturing operations became more productive. The developments in the automobiles at the beginning of the 20th century are instrumental in the growth of a variety of manufacturing methods and practices.

There are a large number of processes available to the engineer for manufacture. These processes can be broadly classified into four categories.

- (a) Casting processes
- (b) Forming processes
- (c) Fabrication processes
- (d) Material removal processes

1.1.1 Casting Processes

These are the only processes where liquid metal is used. Casting is also one of the oldest known manufacturing processes. It requires preparation of a cavity usually in a refractory material to resemble closely the final object to be made. Molten metal is poured into this refractory mould cavity and is allowed to solidify. The object after solidification is removed from the mould. Casting processes are universally used for manufacture of a wide variety of products. The principal process among these is sand casting where sand is used as the refractory material. The process is equally suitable for the production of a very small batch as well as on a very large scale.

Some of the other casting processes for specialised needs are

- shell-mould casting
- permanent-mould casting
- precision-investment casting
- die-casting
- plaster-mould casting
- centrifugal casting

1.1.2 Forming Processes

These are solid state manufacturing processes involving minimum amount of material wastage and faster production. In a forming process, the metal may be heated to a temperature, which is slightly below the solidus temperature and then a large force is applied such that the material flows and takes the desired shape. The desired shape is controlled by means of a set of tools called dies, which may be completely closed or partially closed during manufacture. These processes are normally used for large-scale production rates. These are generally economical and in many cases improve the mechanical properties too.

Some of the metal forming processes are

- rolling
- drop forging
- press forging
- upset forging
- extrusion
- wire drawing
- sheet metal operations

1.1.3 Fabrication Processes

These are secondary manufacturing processes where the starting raw materials are processed by any of the previous manufacturing processes described. It essentially, involves joining pieces either permanently or temporarily so that they would perform the necessary function. The joining can be achieved by either or both of heat and pressure and/or a joining material. Many of the steel structural constructions we see are first rolled and then joined together by a fabrication process.

Some of the processes of interest in this category are

- gas welding
- electric arc welding
- electric resistance welding
- thermit welding
- cold welding
- brazing
- soldering

1.1.4 Material Removal Processes

These are also secondary manufacturing processes where the additional unwanted material is removed in the form of chips from the blank material by a harder tool so as to obtain the final desired shape. Material removal is normally the most expensive manufacturing process because more energy is consumed and also, a lot of waste material is generated in the process. Still this is widely used because it delivers very good dimensional accuracy and good surface finish. It also generates accurate contours. Material removal processes are also called machining processes.

The various processes in this category are

- turning
- drilling
- shaping and planing
- milling
- grinding
- broaching
- sawing

All these manufacturing processes have been continuously developed so as to obtain better products at a reduced cost. Of particular interest is the development of computers and their effect on the manufacturing processes. The advent of computers has made a remarkable difference to most of the above manufacturing processes. They have contributed greatly to both automation and designing the process.

1.2

BREAK-EVEN ANALYSIS

An important responsibility of the engineer is to choose a manufacturing process, which makes the required quality of a product to the specifications and at the lowest cost possible. To fulfil both the conditions, one would have to do a break-even analysis of the various processes suitable for the production of the given object.

In the break-even analysis, two types of costs are considered:

Fixed cost relates to the initial investment on the equipment and tools required for the process. This cost would be constant and does not vary with quantity produced.

Variable cost on the other hand, varies with the actual number of objects made. This takes into account the raw material required, energy consumed, labour cost, cost of special toolings, cost of tools used and other administrative overheads. Requirement of these are directly proportional to the quantity produced.

The total cost of manufacture is thus the sum of both fixed cost and variable cost. This may be written in equation form as

$$TC = FC + VC \times Q$$

where TC = total cost

FC = fixed cost

VC = variable cost per piece

Q = production quantity

The same is shown in graphical form in Fig. 1.1. Normally, as the quantity of production increases, the cost per unit produced decreases. This is due to the fact that the fixed cost associated with the production remains constant.

If the engineer has to make a choice between two different processes for manufacturing the same component, he may first estimate the fixed costs and variable costs for both the processes and then plot the total cost curves for both as in Fig. 1.2. The point where both these curves intersect is called the break-even point. It implies that the first process will be economical if the quantity of production is less than that of the break-even point, that while beyond it the second process is economical.

The break-even quantity, n , can also be obtained by equating the total costs in both the processes. That is,

$$FC_1 + n \times VC_1 = FC_2 + n \times VC_2$$

$$n = \frac{FC_2 - FC_1}{VC_1 - VC_2}$$

This would give a positive value when a fixed cost of a process is greater and a variable cost less than those of the second. If both fixed and variable costs are lower than the other process, then the latter process is always uneconomical whatever may be the production quantity.

Another way of plotting a cost comparison curve is to calculate the average cost of production for different production quantity. The average cost is given by

$$\frac{\text{Total cost}}{\text{Production quantity}}$$

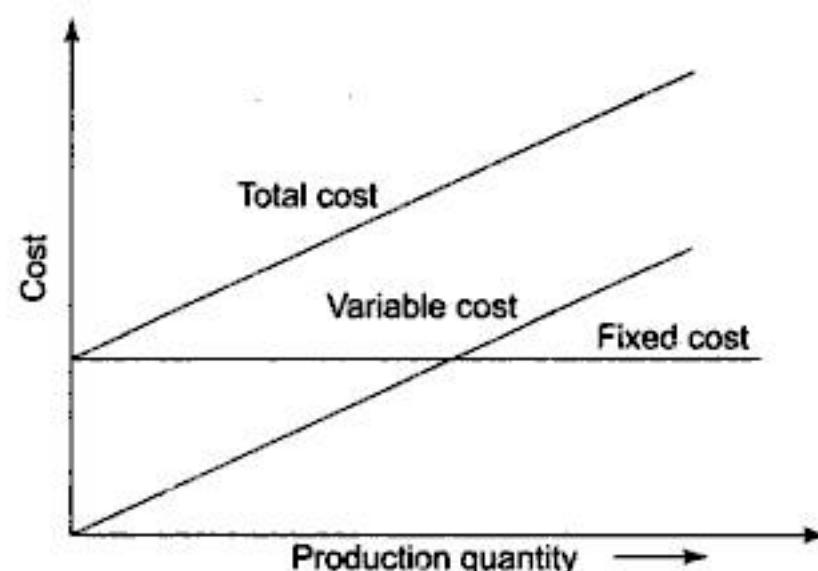


Fig. 1.1 Typical cost curves

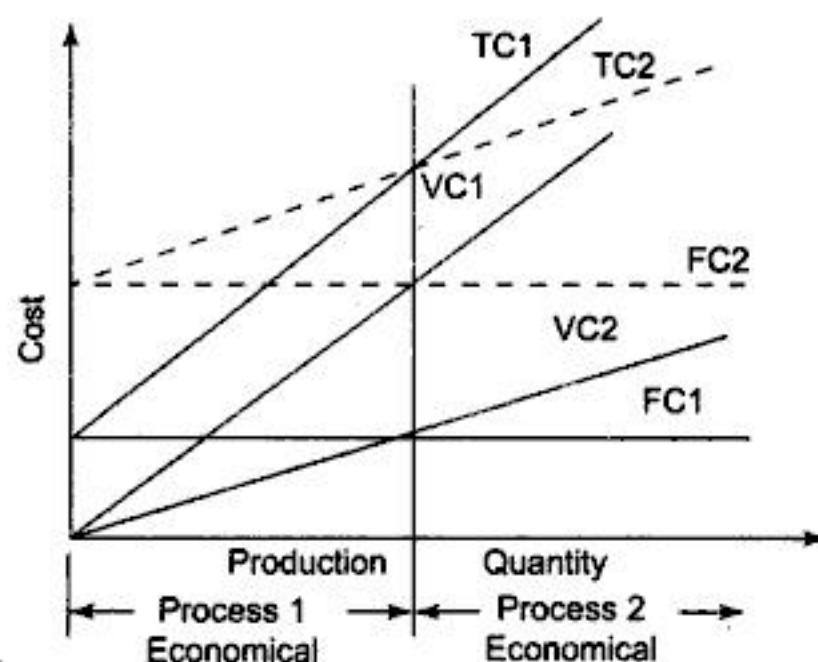


Fig. 1.2 Break-even curve

A typical curve is presented in Fig. 1.3. Alternatively, a base cost for one process could be taken and the curves could be plotted as in Fig. 1.4 for the relative cost per piece vs production quantity. The relative cost can be defined as the cost of the component in relation to any convenient cost such that the abscissa would be represented by more convenient units that is easier to comprehend such as those shown in Fig. 1.4.

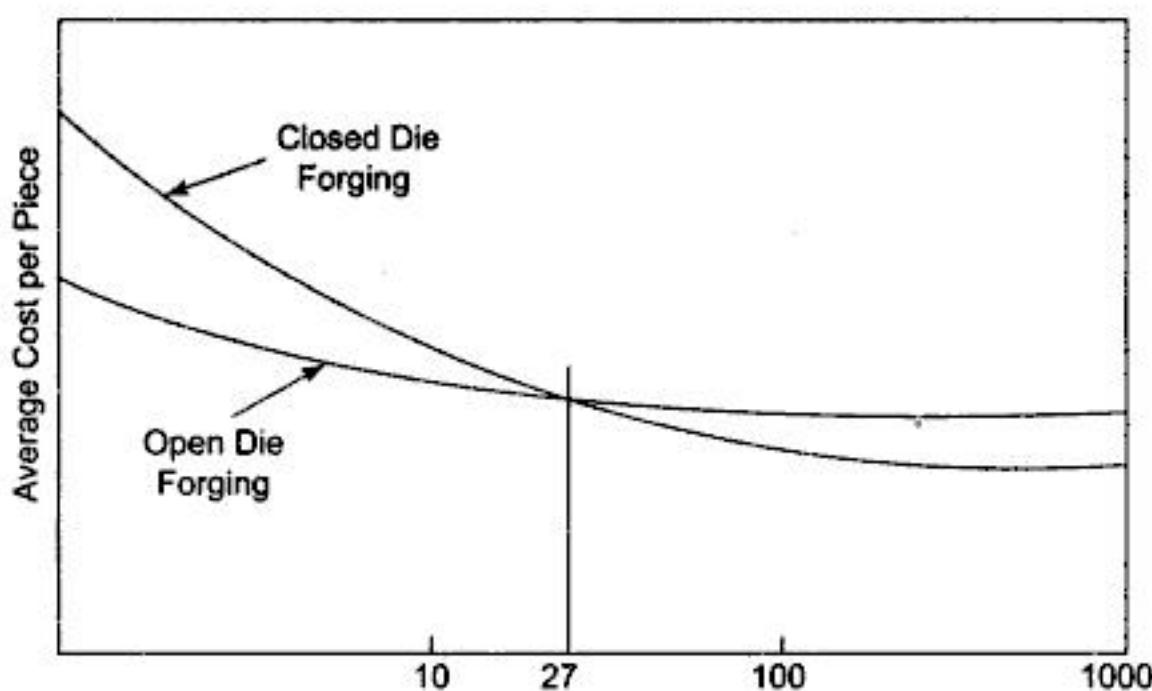


Fig. 1.3 Break-even chart

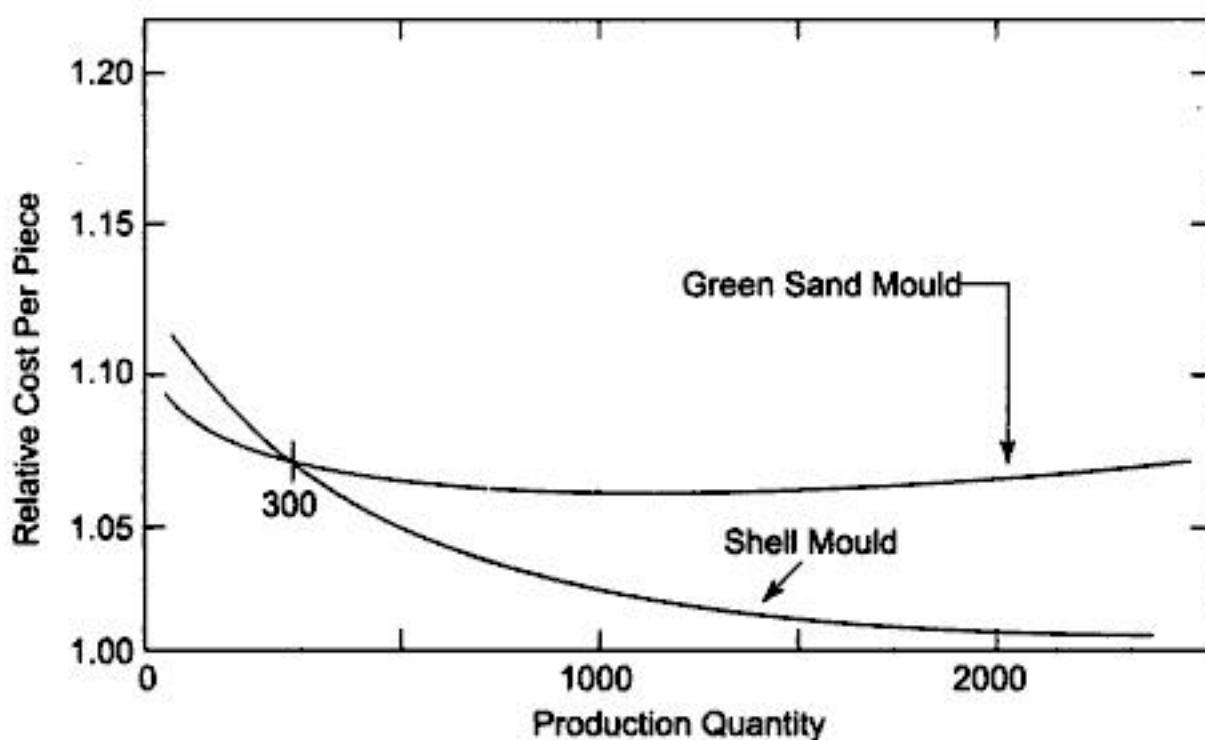


Fig. 1.4 Break-even chart

The manufacturing of a component may involve more than one process or more variants of the same process. In the first case, it is necessary to consider the costs of all the processes while computing the total cost for each of the processes.

|| Example 1.1 || In the manufacture of a machined fitting involving drop forging and machining, there are two options available, the first option is to produce a blocker-type forging followed by heavy machining or a close toleranced forging followed by finish machining. The costs are

	Blocker type (Rs)	Close tolerance (Rs)
<i>Forging</i>		
Die cost	33 500	65 000
Set-up cost	2 500	3 600
Forging piece cost	160	220
<i>Machining</i>		
Tooling cost	86 240	10 000
Set-up cost	7 120	1 080
Running cost	1 600	200

Find out the economical manufacturing method for production quantities up to 1000 pieces.

- Fixed costs are forging die
 forging die set-up
 machining tooling
 machining set-up
 Variable costs are forging piece cost
 machining running cost

	Blocker type (Rs)	Close tolerance (Rs)
Fixed cost	33 500	65 000
	2 500	3 600
	86 240	10 000
	7 120	1 080
Total	129 360	79 680
Variable cost	160	220
	1 600	200
Total	1 760	420

Since in this particular case, both fixed cost and variable cost for close precision forging happen to be lower than the other option, it is economical for any production quantity.

||Example 1.2|| In the production of flap hinges (of titanium) the comparison is to be made between open die forging and blocker type closed die forging. Both these are to be followed by machining. The costs are

	Open die (Rs)	Blocker (Rs)
<i>Forging</i>		
Die cost		93 900
Setup		3 375
Forging piece	35 820	18 150
<i>Machining</i>		
Tooling	93 000	93 000
Running cost	53 625	33 450

Prepare the break-even analysis for the above two variants.

	Open die (Rs)	Blocker (Rs)
Fixed cost		
	93 000	93 900
		3 375
		93 000
Total	93 000	190 275
Variable cost		
	35 820	18 150
	53 625	33 450
	89 445	51 600

Production Quantity	Production cost per piece (Rs)	
	Open die	Blocker
1	182 445	241 875
2	135 945	146 738
3	120 445	115 025
4	112 695	99 169
5	108 045	89 655
10	98 745	70 628
50	91 305	55 406
100	90 375	53 503

$$\text{Break-even quantity} = \frac{FC_2 - FC_1}{VC_1 - VC_2} = \frac{190275 - 93000}{89445 - 51600} = 2.57 \text{ pieces}$$

Summary

Knowledge of manufacturing processes is important to all disciplines in engineering to help in developing better products.

- Manufacturing processes have developed over the years with need for large volumes and variety of consumer requirements.
- To cater to the varying requirements, a number of processes under the broad categories of casting, forming, welding and machining processes have been developed.
- For any given application there can be more than one feasible manufacturing solution. Break-even analysis helps in deciding the most economical solution for a given application.



Questions

- 1.1 Explain why the understanding of manufacturing processes is essential for better products.
- 1.2 Why is it necessary for all engineers to be familiar with manufacturing processes?
- 1.3 What are the broad classifications of the manufacturing processes?
- 1.4 Define break-even analysis.
- 1.5 Describe various ways in which a break-even analysis plot could be made.



Problems

- 1.1 To produce a steel eye the two processes suitable are green sand and shell moulding. The various associated costs are

	Shell (Rs)	Green sand (Rs)
Equipment cost	100 000	35 000
Cost per casting		
Metal cost	3.07	9.00
Moulding cost	6.07	4.85
Cleaning and inspection	2.26	3.83
Overheads	4.04	4.76

Compare the costs of the above two processes with the production quantity ranging from 1 to 10 000.

- 1.2 An aluminium canopy can be obtained by either permanent mould casting or die casting process. The costs in rupees in either case are

	Permanent mould casting	Diecasting
Tooling	112 500	210 000
Set-up cost	202	540
Labour cost	14	10
Material cost	14	7

Find out the break-even quantity of production from 1000 to 15 000 pieces.

(Ans 8894)

2

Engineering Materials

Objectives

After completing the chapter the reader will be able to

- ▶ Understand the importance of the properties of engineering materials such as strength, hardness, ductility, and toughness
- ▶ Learn about the fundamentals of structure of engineering materials and how they control their properties
- ▶ Get the various details of the plain carbon steels and the variables that control their properties
- ▶ Understand the importance of different alloying elements in promoting the properties in alloy steels
- ▶ Learn different non-ferrous materials from the engineering standpoint
- ▶ Understand the heat-treatment process and learn about the various heat-treatment methods and their application

2.1

ENGINEERING PROPERTIES

Manufacturing of a component is normally influenced by the mechanical and thermal properties of the work material. Also, the mechanical properties are affected by the manufacturing process employed. Either way, the knowledge of mechanical properties of engineering materials is important to a manufacturing engineer.

2.1.1 Strength

The resistance offered by a material on application of external force is called strength. Depending on the type of load applied, the strength could be tensile, compressive or shear. By application of load, the material is elastically deformed, which is called strain. It can be defined as

$$\text{Strain} = \frac{\text{Change in dimension}}{\text{original dimension}}$$

The resistance offered by the material is also referred as stress which can then be defined as

$$\text{Stress} = \frac{\text{applied load}}{\text{area of cross section opposing the load}}$$

The deformation caused in a material is of two types, elastic and plastic. *Elastic deformation* is that part of the deformed material which when the applied load is removed, would spring back to its normal shape. *Plastic deformation* is on the other hand, permanently set in a material and cannot be regained.

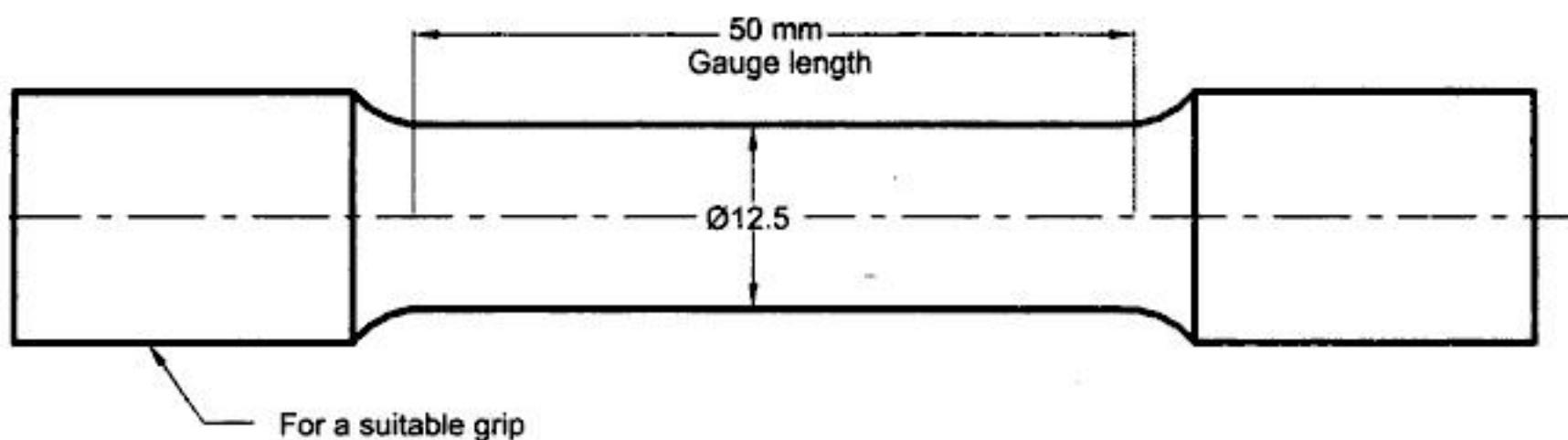


Fig. 2.1 Standard test specimen for tensile test

Tensile strength is measured by a tensile test carried out on a universal testing machine. This involves the preparation of a test specimen as per standard shown in Fig. 2.1. The standard specimen can be either rectangular or cylindrical. Rectangular is generally used for plate-type specimens. Care has to be taken to see that the specimen is prepared in a way such that the surface is smooth and without any deep cracks or nicks.

The tensile testing machine consists of a heavy test frame with a lower fixed beam, and an upper crosshead which is the moving beam used to apply the tensile force on the specimen as shown in Fig. 2.2. The specimen is mounted between two grips, one attached to the fixed beam and the other attached to the crosshead. An extensometer is attached to the specimen to measure the elongation of the test specimen as the force is being applied. Then a uniformly increasing tensile load is applied on the specimen. The movement of the crosshead relative to the fixed beam generates strain within the specimen and a corresponding load. As the load increases, the specimen initially gets elastically elongated. As can be noted from Fig. 2.1, the central portion is smaller compared to the gripping section. On further elongation, the specimen starts necking at some point (within the gauge marks) when the material goes beyond the elastic range. The reduced width of the specimen would further be reduced under the force of the load and finally develop fractures when the test is completed. If the necking does not happen within the gauge marks, the test need to be repeated with a different specimen. During the test, a record is maintained of the load and the corresponding elongation. The stresses and strains are calculated from the above data and plotted in a diagram as shown in Fig. 2.3.

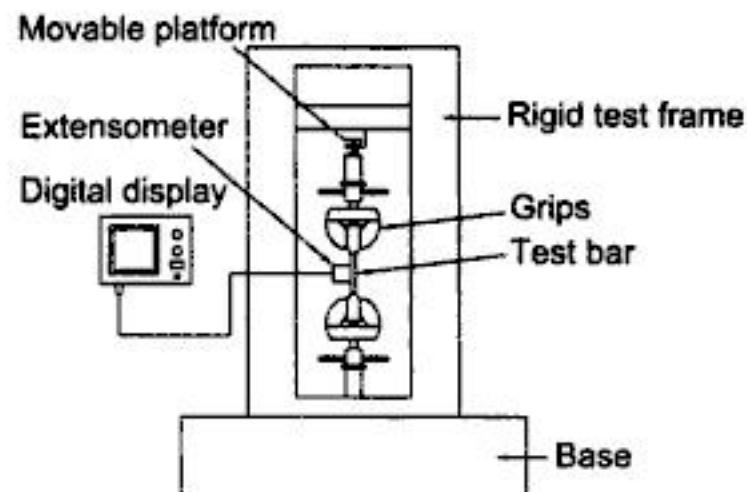


Fig. 2.2 Tensile testing machine

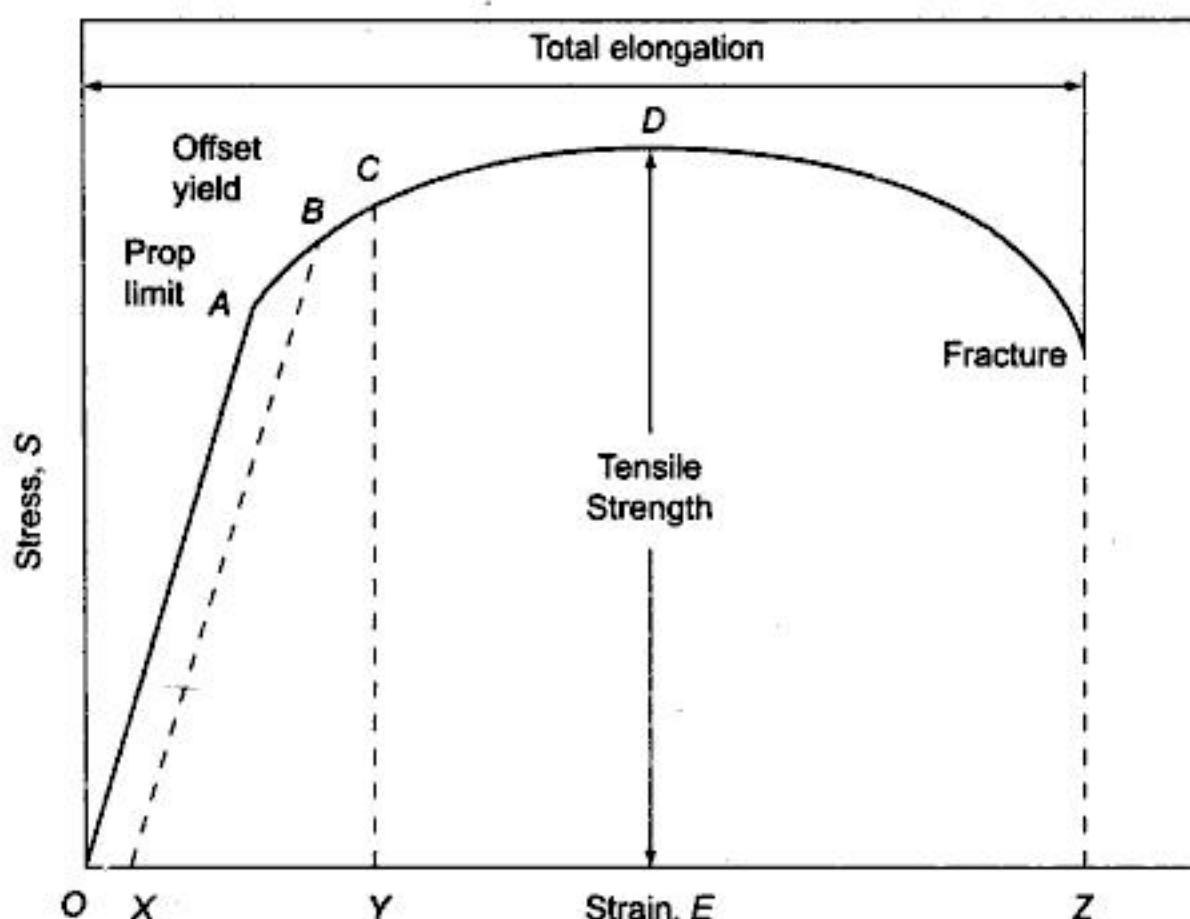


Fig. 2.3 Engineering stress-strain curve (not drawn to scale)

It can be observed that there is a limit up to which the applied stress is directly proportional to the induced strain. This is represented by the linear portion of the curve up to *A* which is termed as the proportional limit. The end of this linear portion is the yield point of the material above which the material starts plastically deforming. In the plastic region, there is a nonlinear relationship between the stress and strain as evidenced by the bow-shaped portion of the curve. Finally, the specimen breaks when the force of the applied load goes beyond the limit that can be borne by the material.

The proportional limit is often difficult to calculate, therefore, two practical measurements, offset yield strength (OYS) and yield by extension under load (EUL), were developed to approximate the proportional limit. Point *B* represents the offset yield strength and is found by constructing a line *X-B* parallel to the curve in the elastic region. Line *X-B* is offset a strain amount *O-X* that is typically 0.2% of the guage length. Point *C* represents the yield strength by extension under load (EUL) and is found by constructing a vertical line *Y-C*. Line *Y-C* is offset a strain amount *O-Y* that is typically 0.5% of the guage length. The ultimate tensile strength, or *peak stress*, is represented by the point *D*. Total elongation, which includes both elastic and plastic deformation, is the amount of uniaxial strain at fracture and is depicted as strain at the point *Z*. Per cent elongation at break is determined by removing the fractured specimen from the grips; fitting the broken ends together and measuring the distance between guage marks. Per cent elongation at break reports the amount of plastic deformation only. The guage length used for measurement is reported with the result.

Similar tests can also be conducted for measuring the compression and shear strength.

2.1.2 Hardness

Hardness is a very important property since the manufacturing depends on it to a great extent. Hardness is the resistance offered by a material to indentation. Moh's scale of hardness is based on ten standard minerals as shown in Table 2.1. It can generally be measured by the indentation made by a harder material. The indentation made depends upon the applied load, the sharpness of the indentor and the time for which the applied load is maintained.

Table 2.1 Moh's scale of hardness

Mineral	Moh's hardness
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

There are a number of indentation tests to measure the hardness of a material normally. These usually involve a ball, a cone or a pyramid of a harder material which is indented into the material under test with a specified load. The permanent indentation thus made is measured to give an indication of the hardness on the given scale for the tests.

The most commonly used tests are the following:

Brinell hardness test where a sphere (usually of diameter $10 + 0.01$ mm) made of steel or tungsten carbide is indented with a gradually applied load at right angles to the specimen surface and the indentation diameter made on the specimen measured. Then the Brinell hardness number, BHN is given by

$$\text{BHN} = \frac{2P}{D[D - \sqrt{D^2 - d^2}]}$$

where P is the applied load in kg,

D is the diameter of the ball in mm, and

d is the diameter of the indentation in mm

The applied load P is based on the hardness of the specimen material being tested.

Some precautions that need to be taken during the use of Brinell tests are that the surface of the material whose hardness is being tested should be smooth and even, and there is enough material underneath the indentation and on all sides to give a proper value for the indentation.

The Brinell hardness of steel is roughly related to the tensile strength of the material utilizing the following empirical relationship for plain carbon steels.

$$\text{Tensile strength (in MPa)} = 3.55 \times \text{BHN} \text{ when } \text{BHN} \leq 175$$

$$\text{Tensile strength (in MPa)} = 3.38 \times \text{BHN} \text{ when } \text{BHN} > 175$$

It may be noted that these conversions are only approximate. Also, the actual relationship depends upon the chemical composition of the alloy as well as the heat treatment process. Comparative values for these are given in Table 2.2.

Table 2.2 Comparison of different hardness scales for steels

Brinell Hardness Number	Vickers Hardness Number	Rockwell Hardness number			Scleroscope hardness	Tensile strength (Approximate) Equivalent MPa
		A Scale	B Scale	C Scale		
578	633	80	—	57	77	2096
555	613	79	—	56	75	2027
555	595	79	—	55	74	1979
534	577	78	—	54	72	1924
514	560	77	—	53	71	1855
495	544	77	—	52	69	1800
495	528	76	—	51	68	1751
477	513	76	—	50	67	1689
461	498	75	—	49	65	1641
444	484	75	—	48	64	1600
444	471	74	—	47	63	1551
432	458	73	—	46	62	1510
415	446	73	—	45	61	1455
415	434	73	—	44	59	1420
401	423	72	—	43	58	1393
388	412	72	—	42	56	1365
388	402	71	—	41	55	1317
375	392	70	—	40	54	1276
363	382	70	—	39	53	1248
352	372	69	—	38	51	1213
341	363	69	109	37	50	1179
331	354	68	109	36	49	1158
331	345	68	108	35	48	1124
321	336	67	108	34	46	1096
311	327	67	107	33	45	1062
302	318	66	106	32	44	1034
293	310	66	106	31	43	1007
285	302	65	105	30	42	979
277	294	65	104	29	41	951
269	286	64	103	28	40	924
262	279	64	103	27	39	903

(Continued)

Table 2.2 (Continued)

Brinell Hardness Number	Vickers Hardness Number	Rockwell Hardness number			Scleroscope hardness	Tensile strength (Approximate) Equivalent MPa
		A Scale	B Scale	C Scale		
255	272	63	102	26	38	869
255	266	63	101	25	37	855
248	260	63	100	24	37	841
241	254	62	99	23	36	814
235	248	62	99	22	35	800
229	243	61	98	21	35	779
23	238	61	97	20	34	765
217	230	—	95	18	33	738
212	222	—	94	16	32	703
203	213	—	92	14	31	676
192	204	—	90	12	29	634
187	195	—	89	10	28	621
179	187	—	87	8	27	600
170	180	—	85	6	26	572
166	173	—	84	4	25	545
156	166	—	82	2	25	531
156	160	—	81	—	25	510
149	156	—	79	—	23	503
143	150	—	77	—	22	483
137	143	—	74	—	21	462
131	137	—	72	—	—	448
126	132	—	70	—	20	427
121	127	—	68	—	19	414
116	122	—	65	—	18	400
112	117	—	—	—	15	386

Rockwell tests utilize the principle that the depth of penetration of the indenter is proportional to the material hardness. Thus, the hardness measurement is faster compared to other methods. In the Rockwell test, a spher-conical diamond cone of 120° angle and a spherical apex of 0.2-mm radius is used to make the indentation, and the depth of the indentation, t , is used as a criterion to calculate the hardness number. The Rockwell hardness number (R) is given by

$$R = 100 - 500 \frac{t}{L}$$

Depending on the load used for indentation there are a number of scales, A, B, C, etc., available in Rockwell tests. These are used for materials with different hardnesses. In the Rockwell B test, a steel ball of 0.0625-inch diameter is used with a load of 100 kg. This test is normally used for low and medium carbon

steels. It should not be used for materials whose hardness is above RB 100. For materials with hardness above this value, Rockwell C test (30 RB corresponds to 0 RC) is more generally used. This is the fastest way of measuring hardness because the hardness can directly be read from the scale on the Rockwell tester.

Besides, there are other tests available such as Vicker's and Knoop hardness tests to measure hardness over a small area. In Vickers hardness test, a square base pyramid diamond indentor having 136° between the opposite faces is used. The Vickers hardness number (VHN) is calculated by

$$VHN = \frac{1.854L}{D^2}$$

where L is the applied load in kg which is normally about 30 kg, though provision up to 120 kg would be available on the testing machine for harder materials, and D is the measured average diagonal of the indentation in mm.

The scleroscope uses a different principle to measure the hardness which is based on the rebound height of a ball from the specimen. The harder the material, the higher is the height to which the ball rebounds.

Because of these hardness tests being conducted under arbitrary conditions, it is difficult to have any proper correlation between the different scales. An approximate relationship of these hardness values is presented in Table 2.2 merely as a guideline.

The hardness values are normally represented as 200 BHN, 32 Rc, etc. Representative values of some commonly used materials are presented in Table 2.3.

Table 2.3 Hardness values of some commonly used materials

Material	Brinell Hardness Number	Rockwell, B
Aluminium	20	
Chromium	125	
Copper		37
Magnesium	46	
Nickel	70	
Tungsten	350	
Iron	70	
C10 steel	105	
C25 steel	126	
C35 steel	163	
C45 steel	179	
C90 steel	197	
30 Mn2 steel	179–235	
32 Mo25 steel	174–217	
60 Si2 steel	184–235	

2.1.3 Ductility

It is the measure of the amount of plastic deformation a material can undergo under tensile forces without fracture. In quantitative terms it is normally measured as the ratio of elongation of the material at fracture during the tensile test to the original length, expressed as a percentage. The final value of elongation obtained

during the tensile test immediately after the fracture could be taken as the ductility. Since the elongation is dependent upon the gauge length chosen for the tensile test, the length needs to be specified along with the elongation values. Alternatively, it may also be expressed as the ratio of reduction in cross-sectional area in the fractured specimen to the original cross-section area. This is independent of the gauge length and hence is a more convenient measure for ductility. It is also termed as the ability of a material to be drawn into wires since only ductile materials can be drawn into continuous wires without breaking in between. Typical values of ductilities are given in Table 2.4 for engineering materials.

Besides the tensile tests, special forms of ductility testing based on the desired application can be done using the bend test and cupping tests for the purpose of sheet metal forming applications. More details of these tests can be found in literature.

Brittleness is the property opposite to that of ductility.

Table 2.4 Ductility values

Material	Ductility, % reduction in area
Cast iron	0
Structural steel	70–40
Cold rolled steel, SAE 1112	45
Cold rolled carbon steels	
C10 steel	57
C20 steel	52
C30 steel	48
C40 steel	40
Steel SAE 1300, annealed	70
Quenched, drawn 700°C	65
Drawn 540°C	60
Drawn 370°C	45
Drawn 200°C	30
Steel SAE 4340, annealed	70
Quenched, drawn 700°C	60
Drawn 540°C	50
Drawn 370°C	48
Drawn 200°C	44
Stainless steel	75–65
Aluminium alloys	35–39
Copper annealed	73
Monel, Ni-Cu alloy	75

2.1.4 Toughness

This is the property which signifies the amount of energy absorbed by a material at the time of fracture under impact loading. In short, it is the capacity to take impact load. It can be considered as the total area under

the stress-strain curve since it is an indication of the amount of work done on the material without causing fracture. Thus toughness can be considered as a parameter consisting of both strength and ductility.

Toughness of a material is measured by means of impact tests, where a notched bar prepared as per standard from the test material, is held in a vice and a weight is allowed to swing from a known height in such a way that it hits the notched bar in its path and breaks it. Since the material has absorbed some amount of energy during its fracture, the swinging mass loses part of its energy and therefore will not be able to reach the same height from where it started, as shown in Fig. 2.4. The loss in height (h) multiplied by the weight represents the energy absorbed by the specimen during fracture, which can be directly measured from the indicator on the tester.

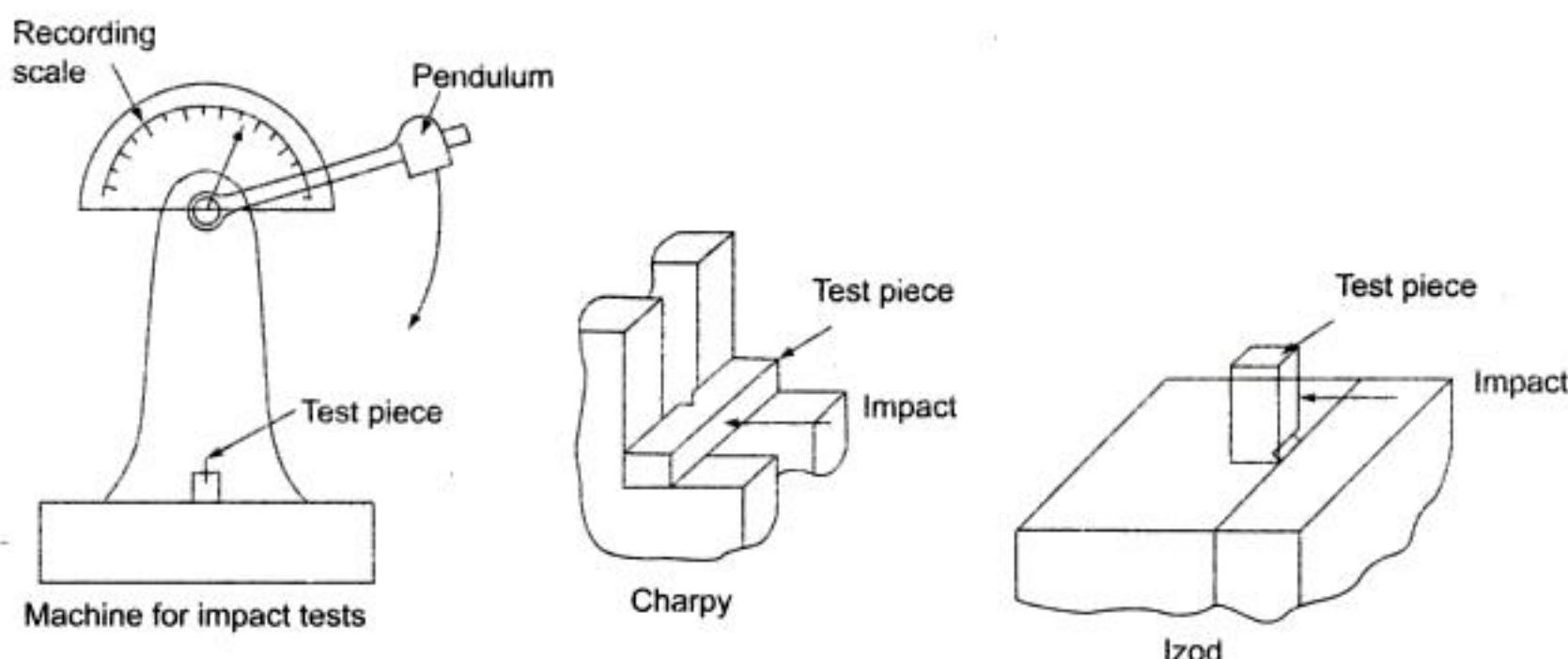
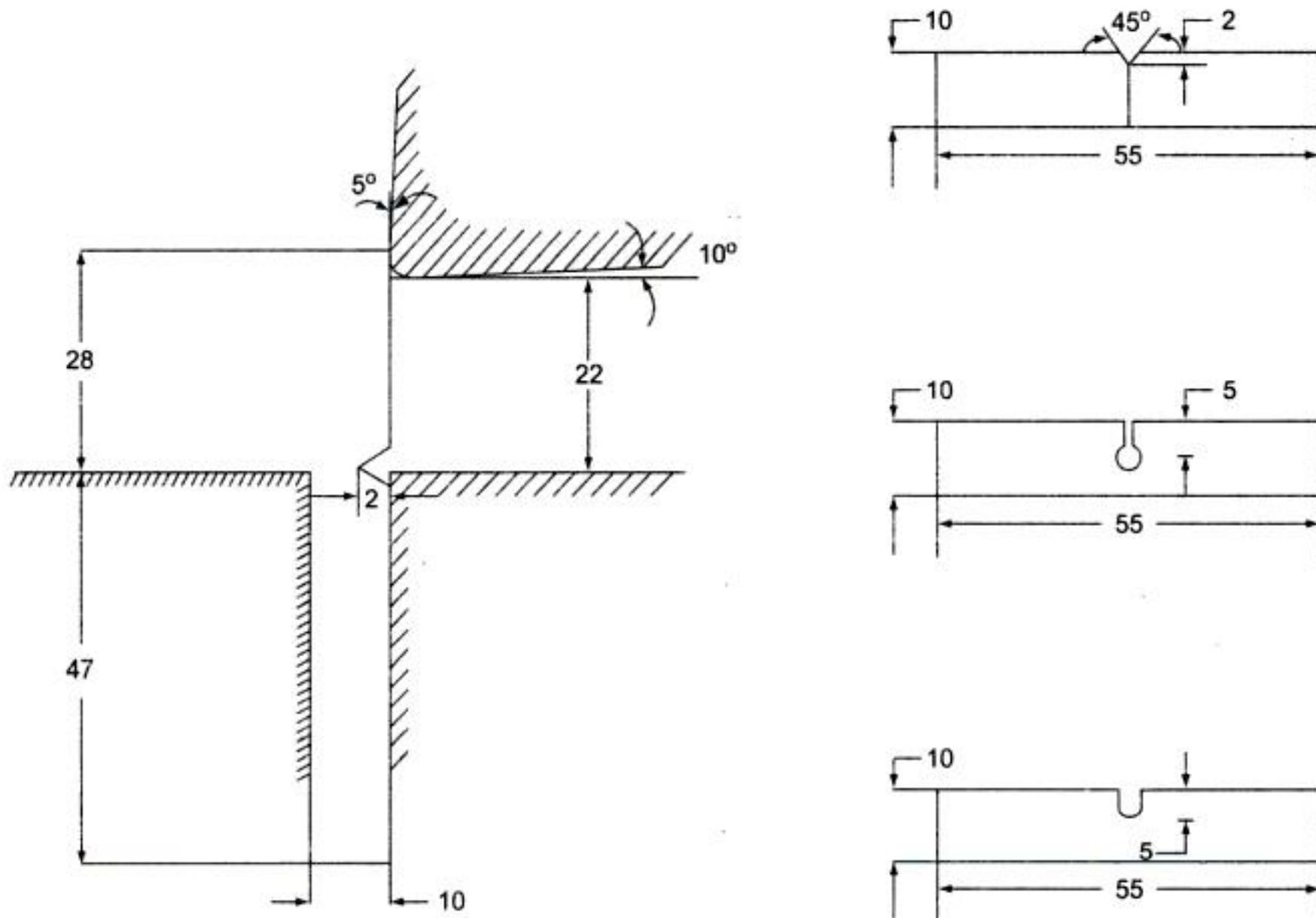


Fig. 2.4 Impact testing machine variations

In the Charpy impact test, the specimen is held between two grips whereas in the Izod impact test the specimen is held at one end like a cantilever as represented in Fig. 2.4. The standard test specimens used in the Izod and Charpy impact tests are made of bars with a square cross section of 10 mm, the details of which are given in Fig. 2.5. The impact resistance is dependent upon the material composition as well as the heat treatment process given to it. The annealed materials normally would have better toughness than the corresponding normalized or quenched specimens. Coarse-grained structures would tend to have higher ductility compared to fine grain structure and consequently better toughness. Typical values of impact resistance measured from these tests are given in Table 2.5 below.

Table 2.5 Toughness values

Material	Toughness, Izod impact value, N m
Steel 20 Mn 2	47
Steel 37 Mn 2	47
Steel 35 Mn 2 Mo 28	54
Steel 40 Cr 1	54
Steel 40 Cr 1 Mo 28	54
Steel 40 Ni 2 Cr 1 Mo 28	54



(a) Specimen mounting for Izod impact test

(b) Standard specimens for Charpy impact test

Fig. 2.5 Standard test specimens for impact tests**2.2****FERROUS MATERIALS**

We use a variety of metals, non-metals and their compounds in our daily life. For example, a typical automobile may contain the following materials:

Steel	1530 kg
Cast iron	350 kg
Rubber	60 kg
Plastic	55 kg
Glass	52 kg
Aluminium	30 kg
Zinc	26 kg
Copper	16 kg
Lead	15 kg
Wood, ceramics, etc.,	in smaller quantities.

Based on their origin and composition these materials may be broadly classified as shown in Fig. 2.6.

Among these, ferrous materials are by far, used most extensively because of their better and varied mechanical properties and lower costs.

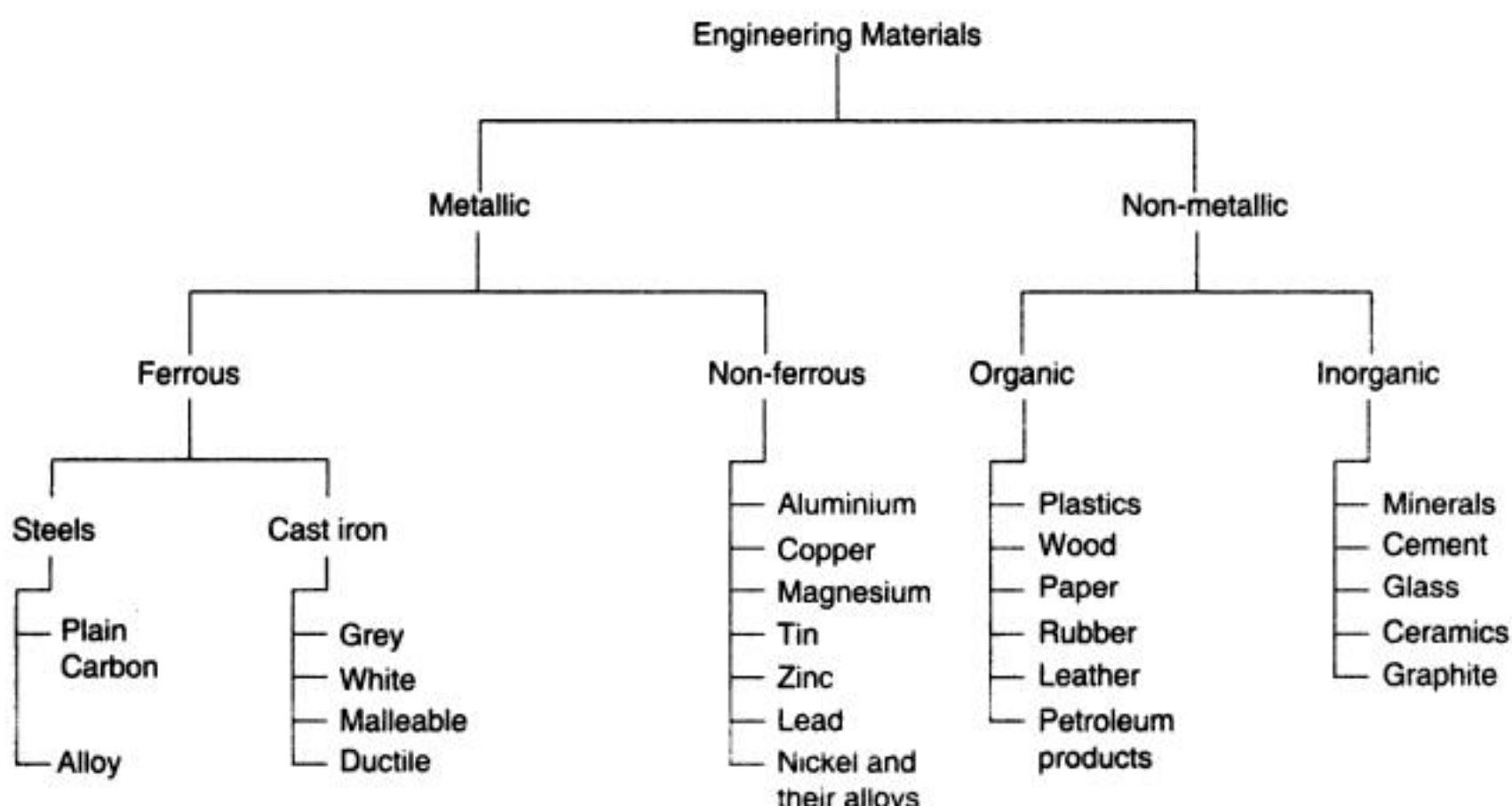


Fig. 2.6 The classification of engineering materials

2.2.1 Iron

The basic source of all iron and steels is iron ore, which is an oxide of iron mixed with alumina, silica, phosphorous, manganese, sulphur and other materials. Major iron ores are haematite and magnetite, which contain about 55% iron.

Pig iron, the principal base material for all steel furnaces, is the product of the blast furnace. Pig iron contains (about 4%) carbon, (1%) silicon, (1%) manganese and smaller percentages of phosphorous and sulphur. Pig iron is hard and brittle. It lacks the great strength, ductility and resistance to shock that steel possesses.

Absolute pure iron is very difficult to obtain. In this state, it is a soft and highly plastic metal of a light grey colour having a specific weight of 7.86. The mechanical properties of commercial grade iron containing 0.1 to 0.2% impurities are

Hardness	60 to 80 BHN
Tensile strength	180 to 310 MPa
Yield point	200 MPa
Reduction in area	75%

The only application that can be found for pure iron is in making of magnets in view of its high permeability. Otherwise, the extensive use of iron is in the form of its large number of alloys. Iron can be alloyed

with many elements. Alloys of iron and carbon are most widely used in engineering. They contain certain amounts of silicon, manganese, chromium, nickel and other elements.

Before proceeding to study the properties of ferrous alloys, a brief survey of the structure of materials would be beneficial for better understanding of the subject.

2.2.2 Structure of Materials

A definite geometrical order is observed in all the crystalline solids in the internal arrangement of atoms and their constituent particles. These particles are located in a solid in such a manner that in the aggregate, they form the space or crystal lattice.

The space lattice of any solid is made of a number of conjugate unit cells inside which the atoms are arranged in a definite order. The definite arrangement of atoms in three dimensions which remains the same throughout the material is called a unit cell. This is the simplest volume which completely fills space, and has all the characteristics of the whole crystal.

Figure 2.7 shows a unit cell of the type called body-centred cubic (BCC) cell wherein atoms are present at all eight corners of the cube and at the body centre. This unit cell is not in isolation but surrounded on all sides by similar unit cells. As a result, the corner atoms are shared by all of the adjacent eight unit cells.

Similarly, there are other arrangements such as face-centred cubic (FCC) and hexagonally close packed (HCP). Iron at room temperature has the structure of BCC with an edge radius (lattice constant) of 0.24824 nm. The following are some of the metals and their unit cell forms.

Face centred cubic Ca, Ni, Cu, Ag, Pt, Au, Pb, Al

Body centred cubic Na, K, V, Mo, Ta, W

Hexagonal close packed Be, Mg, Zn, Cd, Te

Some of the materials exist in more than one form depending upon the temperature. The following is a list of such allotropic forms:

Cobalt

Hexagonal Close packed Below 420°C

Face-centred cubic 420°C to 1495°C

Chromium

Hexagonal Close packed β Below 20°C

Body-centred cubic α 20°C to 1799°C

Pure metals are seldom used as compared to the alloys which are commonly used. Alloys are metallic solids, complex in composition, and are formed as a result of solidification of molten liquid of two or more

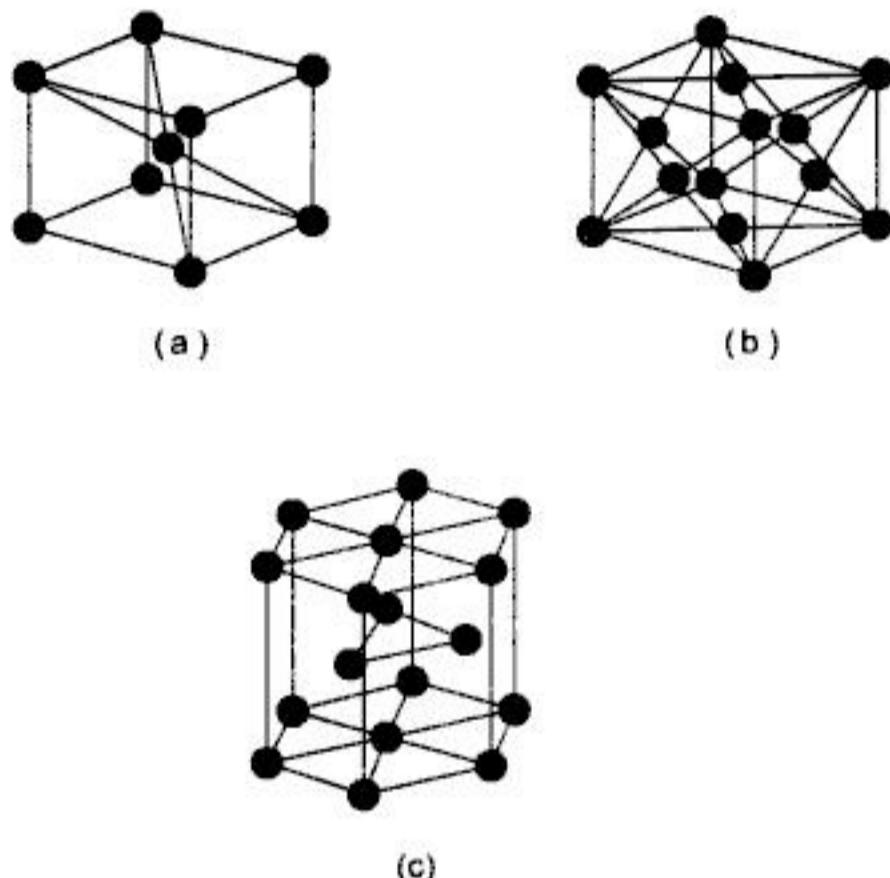


Fig. 2.7 Unit lattice structures; (a) BCC, (b) FCC, (c) HCP

elements. An alloy normally has properties which are a compromise between those of its constituents and sometimes has properties, superior to and quite different from those of its constituents.

Alloys are formed by combining different metals in a number of ways. One predominant form is a solid solution. A solution is formed when solute atoms are dissolved in solvent atoms. Similar to the familiar liquid solutions, it is also feasible to have a solid solution. If a solution is allowed to freeze without separating the constituents, a solid solution would result. In a solid solution, the materials are present only as a mixture but not as chemical compounds. The solid solutions are the essential parts of an alloy.

There are generally two types of solid solutions; one called the interstitial and the other, the substitutional. In an interstitial solid solution, the solute atom would be positioned in the *interstitial sites* (empty space between the adjacent atoms) formed by the solvent atoms. It is possible only when the solvent atom is much larger compared to the solute atom. Also, the extent of solubility depends on the difference in the atomic sizes. For example, carbon would form an interstitial solid solution with iron.

$$\text{Carbon atomic radius} = 0.0750 \text{ nm}$$

$$\text{Iron atomic radius} = 0.1241 \text{ nm}$$

Iron changes to an FCC structure above 720°C . If a carbon atom is placed in the FCC structure of iron at 730°C , the iron atoms are to be displaced by a distance of 0.0430 nm . If a carbon atom is to be located in BCC structure at room temperature, the iron atoms are to be displaced by a distance of about 0.111 nm . Because of this distortion, iron at room temperature would only dissolve a maximum of 0.006% carbon. But above 730°C , up to 2% carbon can be dissolved.

In the substitutional solid solutions, the solute atoms would replace the solvent atoms. This is possible only if both the atoms are similar in size and also in nature.

Diffusion is the process of movement of atoms from one location of higher concentration to another of lower concentration or to a vacant place. Diffusion of atoms would be faster at high temperatures and in liquid phase. It is also a time-dependent phenomenon as the atoms have to physically travel from one site to the other.

In an alloy system, the component metals may combine within a certain temperature range to form two homogeneous coexisting portions. Each of these portions may have different compositions and consequently different properties. These homogeneous physically different portions of the alloy systems are termed as phase. A phase may be defined as any part of a chemical system that possesses distinctive physical characteristics. An alloy may consist of one phase or a combination of different phases. In liquid state, alloys are entirely homogeneous and from the physical point of view, constitute a single phase. Nonhomogeneity may appear when an alloy is transformed from liquid to solid state, i.e., several solid phases may be formed.

Sometimes, when the amount of alloyed metal that can be dissolved in a solid solution is exceeded, the 'parent' metal and the alloyed metal will together form an intermetallic compound. Though the intermetallic compounds are shown with a chemical symbol such as Fe_3C , they are not like the chemical compounds such as CO_2 , which are actually formed by a chemical reaction. In the present case it is only an atomic arrangement. Intermetallic compounds are usually very hard. Even if only a small amount of intermetallic compound is present, the alloy will combine the toughness of a solid solution with the hardness of the intermetallic compound.

Eutectic Composition In certain alloy systems, alloying causes a lowering of the melting points and at a certain composition, called the *eutectic composition* for the system, the melting point is the lowest. For

example, the alloy of 62% tin and 38% lead has a melting point of 183°C whereas lead melts at 327°C and tin melts at 232°C as in Fig. 2.8. The low melting point of this alloy called solder enables delicate parts of metal to be soldered without damage by heat.

Equilibrium Diagrams A cooling curve is drawn with temperature against time for a given metal or alloy showing the phases present in it. But for an alloy system containing various compositions of the constituent elements, it is necessary to draw a phase diagram or equilibrium diagram wherein the phases found at various temperatures and compositions are plotted in a single chart. The equilibrium diagrams are thus the generalized results of investigations into the solidification process and the structural and phase transformation of the given alloy system.

These diagrams enable to determine the temperature levels at the beginning and end of melting for alloys of various compositions, the structure of alloys for various temperatures under equilibrium conditions and also the transformation the alloys are subjected to during cooling and heating. Equilibrium conditions mean that sufficient time would be available for the changes of phases to take place.

An equilibrium diagram is plotted by laying off the percentage concentrations of the two components along the abscissa and the temperature along the ordinate. Any point on the diagram refers to a definite composition of the alloy at a particular temperature, as shown in Fig. 2.8.

Nucleation and Grain Growth When the free energy of a parent phase is reduced by means of temperature or pressure then there is a driving force leading to crystallization. For example, at the melting point, the thermal fluctuations result in the formation of tiny particles (containing only a few atoms) of the product phase within the parent volume. Such a tiny particle has an interface that separates it from the parent matrix. It grows by transfer of atoms across its interface.

The process of formation of the first stable tiny particles is called *nucleation*.

The process of increase in the sizes of these particles is called *grain growth*.

The grain size in the product phase depends on the relative rates of nucleation and growth. Each nucleating particle becomes a grain in the final product. So a high nucleation rate means a larger number of grains. Also, when this is combined with a low growth rate, more time is available for further nucleation to take place in the parent phase that lies between slowly growing particles. So a combination of a high nucleation rate and a low growth rate yields a fine grain size. On the other hand, a low nucleation rate combined with a high growth rate yields a coarse grain size.

The temperature of maximum rate of nucleation is lower than the temperature of maximum growth rate. An increase in cooling rate lowers the effective transformation temperature and results in the combination of

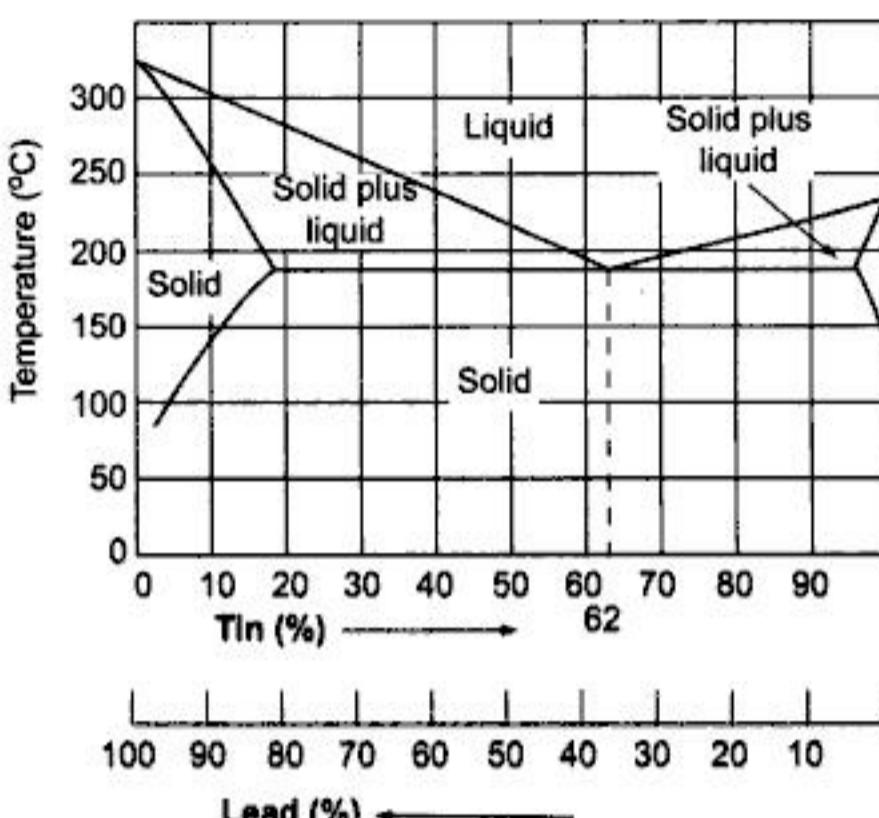


Fig. 2.8 Equilibrium diagram of lead-tin system

a high nucleation rate and a relatively slow growth rate and, ultimately, yields a fine grain size. A representation of grains is presented in Fig. 2.9. In this figure, each square represents a unit cell.

Coarse grain steels are not as strong and have a higher tendency towards distortion than those having fine grain, although they offer better machinability and greater depth hardening qualities. Fine grained steels are tougher and more ductile and do not distort or crack during heat treatment.

2.2.3 Plain Carbon Steels

As has been mentioned earlier, iron in its purest form is not used as an engineering material because it lacks tensile strength and hardness. But when alloyed with other elements, the properties can be controlled greatly. Out of the various alloying elements, carbon is the most important because it is found in all the alloys of iron.

The maximum amount of carbon that can be alloyed with iron is 6.67%. Alloys containing up to 2% carbon are termed steels and above 2% are called cast irons. Besides carbon, these alloys also contain small amounts of manganese, sulphur, phosphorous and silicon. These are generally considered as impurities and hence need to be controlled. However, in certain conditions some of these such as silicon are treated as alloying elements.

The properties of steel are influenced significantly by an increase in carbon content (Fig. 2.10) with a result that

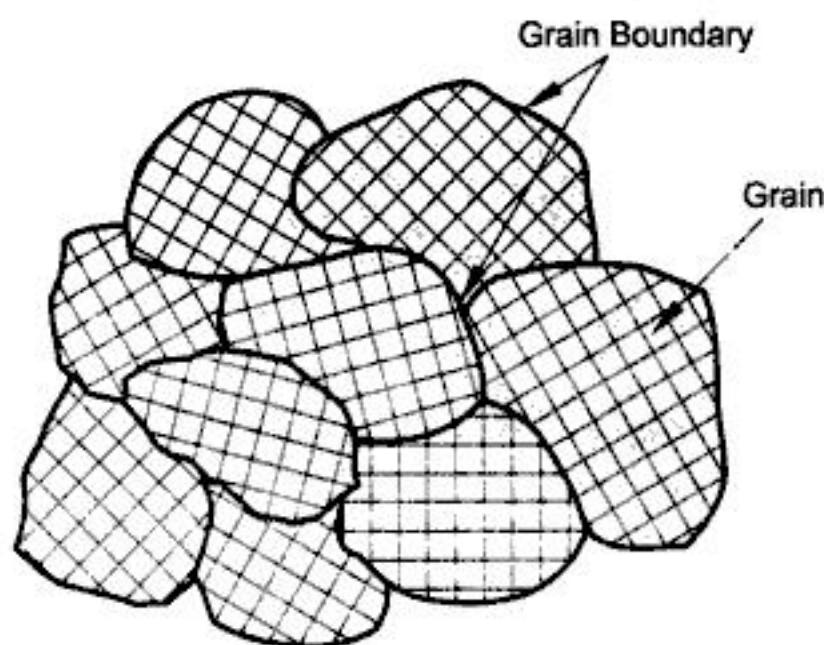


Fig. 2.9 Grain representation

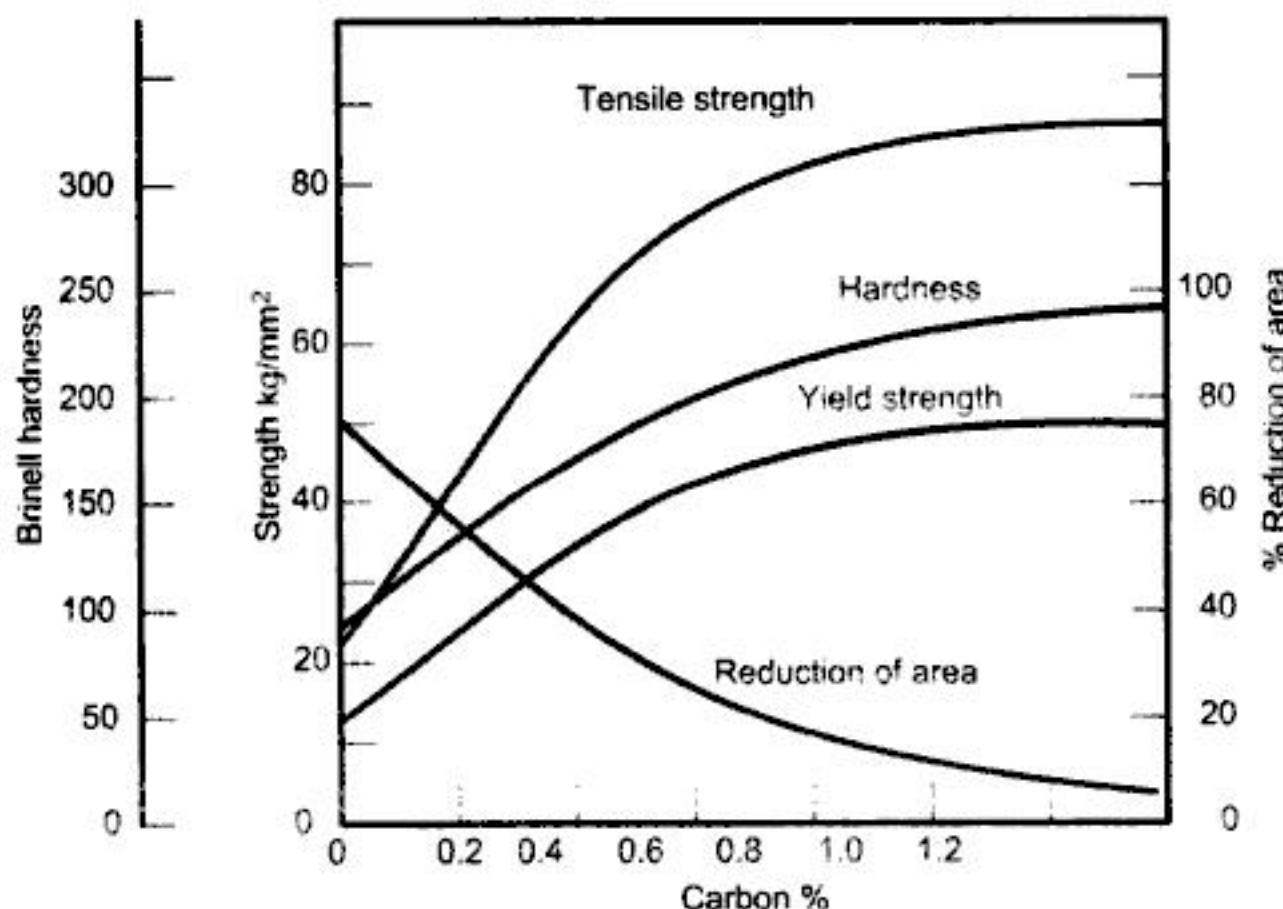


Fig. 2.10 Effect of carbon on mechanical properties of steels

- (i) tensile strength is increased,
- (ii) greater hardness is obtained,
- (iii) ductility is decreased, and
- (iv) weldability is decreased.

A point however to be noted is that in all steels even when alloyed with other alloying elements, the maximum hardness that can be obtained after heat treatment processes is basically a function of the carbon content.

There are three classes of steels (plain carbon):

Low	up to 0.30% C
Medium	0.30 to 0.60% C
High	0.60 to 1.70% C

Low Carbon Steel This is generally known as 'soft' or mild steel. It is used where ductility and softness are important and high tensile strength is not required. These are tough but not resistant to wear, since these are soft, can be very easily formed and later can be carburized to increase the hardness and wear resistance.

Low-carbon steels are used for such operations as spinning, cold bending, rivetting, swaging, etc. These are not responsive to normal heat treatment but for case hardening. They form the largest percentage of steel produced, being the cheapest engineering material. Products such as screws, nails, nuts, bolts, washers, wire fences, light and heavy structural members, machine parts, forged parts can be made from low-carbon steel. It is also used for tin plate and automobile body sheet. It is available in form of sheets, squares, rounds, plates, and wires.

Medium Carbon Steel They are less ductile but harder and have greater tensile strength than low-carbon steels. They also have better machining qualities and are more responsive to heat treatment.

These are widely used in the industry. Medium carbon steels are used for making shafts, connecting rods, spindles, rail axles, gears, turbine bucket wheels, steering arms and other machine parts requiring medium strength and wear-resisting surfaces.

High Carbon Steel They have higher tensile strength and are harder than other plain-carbon steels. They also readily respond to heat treatment. These are used for making hand tools such as wrenches, chisels, punches, files, cutting tools such as drills, wood-working tools, railroad wheels, rails, bars for reinforcing of concrete, etc.

Effect of Small Quantities of Other Elements In addition to carbon, the plain carbon steels contain small quantities of other elements more as impurities. They affect the properties in the following way.

Sulphur Iron forms iron sulphide, FeS with sulphur which solidifies along the grain boundaries making the steel brittle and lowers hot working properties such as ductility. If equal amount of manganese is present in the steel then manganese sulphide, MnS, forms and the harmful effects of sulphur are reduced. It is generally recommended that manganese should at least be 3 times that of sulphur. However, very small quantities (0.075 to 0.15%) that are generally present contribute to the better machinability.

Phosphorous Phosphorous in small amounts increases the strength and hardness of steels. Most of the steels contain a very small percentage of about 0.05% phosphorous.

Silicon Silicon in very small amounts of the order of less than 0.2% do not have any effect. When it is between 0.2 and 0.4%, it raises the elastic limit and ultimate strength of the steel without greatly reducing the ductility. More than this percentage it reduces the ductility.

The main limitations of plain carbon steels are

- Low hardenability
- Loss of hardness during tempering
- Low strength at elevated temperature
- Lower resistance to corrosion and oxidation

Alloy steels have been specifically developed to overcome these limitations and they are discussed later in this chapter.

2.2.4 Iron-Carbon Equilibrium Diagram

The structural form of pure iron at room temperature is called ferrite or α -iron. Ferrite is soft and ductile. Since ferrite has a body-centred cubic structure, the inter-atomic spaces are small and pronouncedly oblate, and cannot readily accommodate even a small carbon atom. Therefore, solubility of carbon in ferrite is very low, of the order of 0.006% at room temperature. The maximum carbon content in ferrite is 0.05% at 723°C. In addition to carbon, a certain amount of silicon, manganese and phosphorous may be found in ferrite.

The face-centred modification of iron is called austenite or γ -iron. It is the stable form of pure iron at temperatures between 910°C and 1400°C. At its stable temperature austenite is soft and ductile and consequently, is well suited for manufacturing processes. The face-centred cubic structure of iron has larger inter-atomic spacing than in ferrite. Even so, in FCC structure the interstices are barely large enough to accommodate carbon atoms, and lattice strains are produced. As a result, not all the interstitial sites can be filled at any one time. The maximum solubility is only 2% of carbon at 1130°C.

Above 1400°C, austenite is no longer the most stable form of iron, and the crystal structure changes back to a body-centred cubic phase called δ -iron. This is the same phase as the α -iron except for its temperature range. The solubility of carbon in δ -ferrite is small, but it is appreciably larger than in α -ferrite, because of higher temperature. The maximum solubility of carbon in δ -iron is 0.1% at 1490°C.

In iron-carbon alloys, carbon in excess of the solubility limit must form a second phase, which is called iron carbide or cementite. Iron carbide has the chemical composition of Fe_3C . This does not mean that iron carbide forms molecules of Fe_3C , but simply that the crystal lattice contains iron and carbon atoms in a three-to-one ratio. The compound Fe_3C has an orthorhombic unit cell with twelve iron atoms and four carbon atoms per cell, and thus has a carbon content of 6.67%.

As compared to austenite and ferrite, cementite being an inter-metallic compound, is very hard and brittle. The presence of iron carbide with ferrite in steel greatly increases the strength of steel.

The iron-carbon equilibrium diagram is shown in Fig. 2.11. The solidification of the liquid iron and carbon melt begins along the liquidus denoted in the figure by ABCD. Above the liquidus, the alloy is in a liquid state and is a homogeneous system. Along the liquidus AB, the crystals of the solid solution of carbon in γ -iron are separated from the liquid.

Crystals of austenite are separated from the liquid along the line BC with the compositions ranging from 0.18% to 2.0%. The complete solidification of these alloys proceeds along the solidus line HJCE. Alloys containing 0.18 to 2.0% carbon become solid along the solidus HJE. Those with 2.0% to 4.3% carbon are

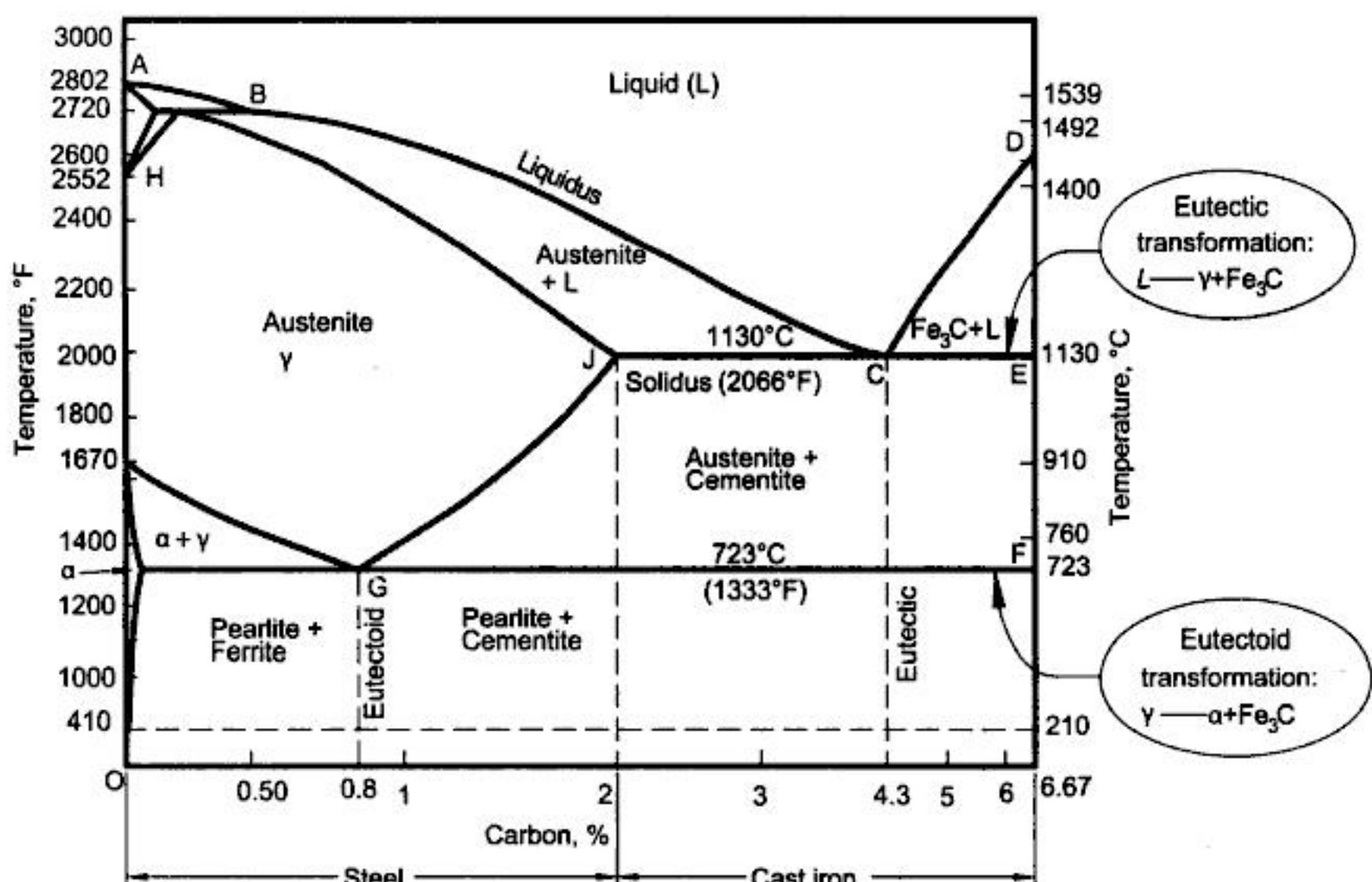
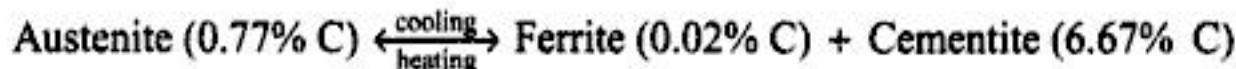
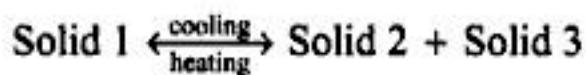


Fig. 2.11 Iron–carbon equilibrium diagram

completely solidified on line *EC*. The solidification of the last portion of the liquid phase, enriched in carbon to 4.3% takes along this line. All this liquid is completely solidified at 1130°C; at the same time crystals of austenite containing 2% carbon and cementite containing 6.67% carbon get separated from it. The solidification of alloys containing 4.3% to 6.67% carbon begins along line *CD*, with the separation of primary cementite from the melt.

At the lower temperatures, the eutectoid reaction, i.e., formation of two solids from a single solid occurs at a temperature of 723°C. This is called the *eutectoid temperature* and the composition at which this reaction occurs (0.80% C) is called the *eutectoid composition*. The reaction may be shown as follows:



In the reaction, the simultaneous formation of ferrite and cementite from austenite results at the temperature of 723°C and composition of 0.80% carbon. There are nearly 12% of iron carbide and slightly more than 88% of ferrite in the resulting mixture. Since the ferrite and cementite are formed simultaneously, they are intimately mixed. Characteristically, the mixture is *lamellar*, i.e., it is composed of alternate layers of ferrite and cementite. This micro-structure is called *pearlite* which is very important in iron and steel technology, because it can be formed in almost all steels by means of suitable heat treatments.

The alloy containing 0.80% of carbon is called the *eutectoid steel*. Upon cooling the eutectoid steel below 723°C, all of the austenite is transformed into pearlite. Alloys with less than 0.80% C are called *hypo-eutectoid steels* and those with higher composition are called *hyper-eutectoid steels*.

When hyper-eutectoid steels are cooled below line SE, the austenite decomposes with the separation of cementite. Since this cementite contains 6.67% C, the carbon concentration in the remaining austenite changes continuously along the line SE until the eutectoid composition of 0.80% C.

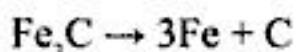
2.2.5 Cast Irons

The ferrous alloys which have carbon contents of more than 2% are called *cast irons*. Though cast irons can have a carbon percentage between 2 to 6.67, the practical limit is normally between 2 and 4%. These are important mainly because of their excellent casting qualities.

From the iron–carbon equilibrium diagram (Fig. 2.11), it can be observed that cast irons have essentially cementite and ferrite. Because of the larger percentage of carbon, the amount of cementite is high resulting in very high hardness and brittleness qualities for cast iron.

When cast iron is slowly cooled, the cementite decomposes into iron and carbon in the form of graphite which is called *graphitization*. Cast irons where a large percentage of cementite is decomposed by graphitization are called *grey cast irons*. Cast iron in which graphitization has not taken place, i.e., all the carbon is in the combined form, is called *white cast iron*. The graphitization process requires time and therefore, when liquid cast iron is cooled rapidly, white cast iron would result. White cast iron is comparable in properties to that of high carbon steels. However, it is highly brittle and as such is not used for structural parts. It is useful for parts where abrasive wear is present. Tensile strength varies between 170 to 345 MPa and is usually about 240 MPa. The hardness ranges from 350 to 500 BHN. In view of the very high hardness, the machinability is poor and is commonly finished by grinding.

In the presence of graphitizing elements such as nickel and silicon, iron carbide decomposes as follows:



The decomposition is controlled by the graphitizing agents as well as the cooling rate.

The dissociated carbon is in the form of graphite which is very soft and without any strength. Thus, it reduces the hardness and increases the machinability of cast iron. The shape of graphite present in cast irons would greatly affect its strength. When it is in a flake-like shape as in grey cast iron, the graphite breaks up continuity of iron and greatly weakens it. But it also helps in absorbing vibrational energy, as a result of which grey cast iron is normally used for the beds of machine tools. Grey cast iron is easily machinable and is the cheapest form of cast iron. Because of its low melting temperature, higher fluidity and negligible shrinkage on cooling, it is extensively used in casting processes.

The other form of cast iron is known as malleable iron in which free carbon is present in the form of nodules in the matrix of cementite and ferrite. This is achieved by first chilling the casting so that all white cast iron is formed, followed by a controlled heat treatment process so that some of the cementite is transformed to ferrite and nodules of free carbon. This material is more ductile than grey cast iron. This form is suitable only for components with very small section thicknesses since all white cast iron is to form the starting point for malleable iron.

When graphite is present as small, round, and well-distributed particles, its weakening effect is small and such cast irons would have higher ductility. This type of cast iron is called ductile or nodular iron or spheroidal graphite or simply SG iron. This form of graphite can be achieved by adding elemental magnesium or cerium or a combination of the two elements to molten cast iron. Magnesium is added in quantities of 0.07 to 0.10% followed by the addition of ferro-silicon to promote graphitization. During solidification, magnesium helps in the distribution of graphite throughout the metal.

Ductile iron has better strength-to-weight ratio, better machinability and higher impact value. Moreover, the ductile iron components are produced by casting process wherein better control of component shape can be achieved compared to drop forging. Thus, many a component such as crank shafts and connecting rods manufactured usually by drop forging is increasingly being replaced by ductile iron castings. Typical comparison of different casting materials is given in Table 2.6.

Table 2.6 Comparative properties of cast irons

Property	Grey cast iron	Malleable iron	Ductile iron	C30 steel
Melt temperature, °C	1 175	1 200	1 150	1 450
Specific gravity, kg/m ³	6 920	6 920	6 920	7 750
Vibration damping	Excellent	Good	Good	Poor
Modulus of elasticity, MPa	126 174	175 126	173 745	210 290
Modulus of rigidity, MPa	48 955	70 329	66 190	78 600

2.2.6 Other Alloying Elements

Steel is an alloy of iron. Normally, ferrous alloys containing only carbon as the alloying element are called *plain carbon steels* or simply steels while those containing besides carbon, some other alloying elements such as chromium, are termed *alloy steels*. In fact, the definition given by American Iron and Steel Institute (AISI) is as follows:

Steel is considered to be alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65%; silicon, 0.60%; copper, 0.60%; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognised field of constructional alloy steels: aluminium, boron, chromium up to 3.99%, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect.

The alloy steels are normally required when additional properties such as strength, ductility, toughness or corrosion resistance are desirable in large measures. The various ways in which special alloying elements are used to improve the properties of steels are the following:

1. To improve hardenability
2. To improve mechanical properties at low or elevated temperatures
3. To improve the corrosion and oxidation resistance
4. To increase the machinability
5. To increase the electrical and magnetic properties
6. To increase resistance to softening on tempering
7. To increase abrasion resistance
8. To increase hardness of steels that cannot be quenched

Since the micro-structure essentially consists of ferrite and cementite, the mechanical properties can be controlled by changing either the properties of carbide and ferrite phases by the alloying elements or by controlled dispersion of carbide in the ferrite matrix. The carbide phase present in alloy steels is not pure iron carbide but a complex combination of iron and alloy carbides. Some of the alloying elements act as *austenite stabilisers*. An austenite stabiliser lower the eutectoid temperature thereby expanding the temperature range in which austenite is stable.

The effect of alloying elements can also be described by means of the following empirical relationships which show the critical temperatures in the iron-carbon equilibrium diagrams. Ac_1 refer to the boundary between austenite and pearlite, while Ac_3 refers to the temperature separating austenite with austenite and cementite.

$$Ac_1 = 723 - 10.7 \text{ Mn} - 16.9 \text{ Ni} + 29.1 \text{ Si} + 16.9 \text{ Cr} + 290 \text{ As} + 6.38 \text{ W}$$

$$Ac_3 = 910 - 203\sqrt{\text{C}} - 15.2\text{Ni} + 44.7\text{Si} + 104\text{V} + 31.5\text{Mo} + 13.1\text{W}$$

Out of the various alloying elements, nickel, silicon and aluminium do not form any carbides whereas manganese, chromium, tungsten, molybdenum, vanadium, titanium and niobium have increasing carbide stability in that order. When nitrogen is present, many of these carbide formers form carbo nitrides or nitrides which are highly abrasion resistant. The following is a detailed account of the effect of individual alloying elements on the mechanical properties of alloy steels.

Manganese This is the most common alloying element in all steels. It decreases the critical temperatures appreciably and thus lets the steel oil harden. Also, it is a cheap way of increasing the hardenability of steels. It forms a carbide Mn_3C but its carbide-forming tendency is the lowest of all alloying elements. It counteracts the brittleness caused by sulphur in steels. Equal amounts of manganese and sulphur in steel form manganese disulphide readily, which is evenly distributed in it. This greatly improves the hot working characteristics and also the lubrication in machining ensuring good surface finish. Manganese in amounts of 2 to 10% imparts brittleness to steel. The particular composition of 11 to 14% manganese and 1 to 1.4% carbon has got a very high resistance to wear and abrasion even under high impact stresses. With such large manganese content the critical temperature is reduced and martensite could be obtained even with slow cooling during quenching. Very rapid quenching allows for retained austenite, thus giving it high ductility and toughness. This is quite useful for service involving continuous impact loads but not suitable for abrasive loads.

Chromium It is a strong carbide former and forms complex series of carbide compounds of chromium and iron. It raises the critical temperature appreciably and thus resists tempering. It increases hardenability, wear resistance, corrosion and oxidation resistance. The primary use of chromium in steels, thus, is because of its high hardness and corrosion resistance.

Nickel Nickel is not a carbide former but strengthens and toughens the ferrite phase. It reduces the critical cooling rate required for quenching and therefore they can be very easily heat treated. It increases the tensile strength without appreciable decrease in elongation and decrease in area. In many ways its effect on properties is similar to manganese. In combination with chromium, it provides high elastic ratios, greater hardenability, higher impact and fatigue resistance.

Tungsten It is a very strong carbide former and forms abrasive resistant particles in tool steels. At larger percentages it improves hot hardness and hot strength and as such is useful in cutting and hot working tools. It is not softened by tempering. In tungsten steels, much higher tempering temperatures may be employed with less loss in hardness with reduction in internal strains compared to plain carbon steels.

Molybdenum It greatly increases the hardenability. It is also a strong carbide former. It increases the hot hardness and hot strength when used in combination with chromium and vanadium. Since molybdenum is cheaper than tungsten, it is replacing tungsten to a great extent in tool steels. It raises the critical temperature for tempering and so does not soften even at a higher temperature. The typical amounts present are 0.15 to

0.50% molybdenum in general tool steels. The main problem with molybdenum is the promotion of skin decarburization which is to be properly accounted for during heat treatment.

Vanadium It is a strong carbide former. It increases the hardenability and also the secondary hardening effect upon tempering. Grain growth tendency at heat treating temperatures is minimized. Vanadium steels have a much finer structure than steels without vanadium. It increases hardness at elevated temperatures.

Silicon It slightly increases the hardenability. It sustains hardness during tempering. One of the important use of silicon is as a deoxidiser in molten steel and for its ability to resist oxidation in steel. In large quantities above 2.5%, it increases the strength of the ferrite phase without affecting its ductility. But at this percentage it develops poor machinability and is susceptible to decarburization. Silicon increases the electrical resistivity of iron thus reducing eddy current effects with alternating current. Thus, silicon steels are used extensively for electrical applications. Silicon steels can be easily magnetized in a direction parallel to their crystallographic cubic edge. By a careful combination of rolling and annealing, it is possible to align the grains in the desired direction. Thus silicon steels are also used for magnetic applications.

Aluminium It is primarily used as a deoxidizer in steels. It is most effective in inhibiting grain growth. In those steels which are to be nitrided, aluminium provides an extremely high hardness of the nitrided case due to the formation of hard and stable aluminium nitride compound.

Titanium It has the highest carbide-forming tendency of all the alloying elements. It has no effect on hardenability. It is a good deoxidizer and inhibits grain growth. Because of its strong carbide forming tendencies, medium carbon steels do not quench harden.

Niobium Also called 'columbium', it reduces the hardenability and increases the ductility slightly which results in a marked increase in impact strength. It imparts a fine grain structure to steels and retards softening during tempering.

Cobalt It decreases the hardenability. Cobalt strengthens ferrite when dissolved in it and resists softening under elevated temperatures. It promotes skin decarburization.

The comparative effect of the alloying elements on the hardness of alloy steels is presented in Fig. 2.12. It can be seen from this figure that the effect of each alloying elements is different and the effect is also pronounced by an increase in the composition percentage.

2.2.7 Steel Designation

To refer materials, there are a number of ways based on standard specifications. The following are some of the most commonly referred designations.

Indian Standard Designation Among plain carbon steels, the structural steels where no heat treatment is required, are designated by its tensile strength in kgf/mm², e.g., st 42 means a structural steel with a minimum tensile strength of 42 kgf/mm².

Other plain carbon steels having carbon as the chief alloying element, are referred by its chemical symbol C followed by a number representing its percentage in hundredths. For example, C20 refers to a plain carbon steel with an average carbon percentage of 0.20. If sulphur and phosphorous are to be denoted as limited, a suffix K would follow, e.g., C25K.

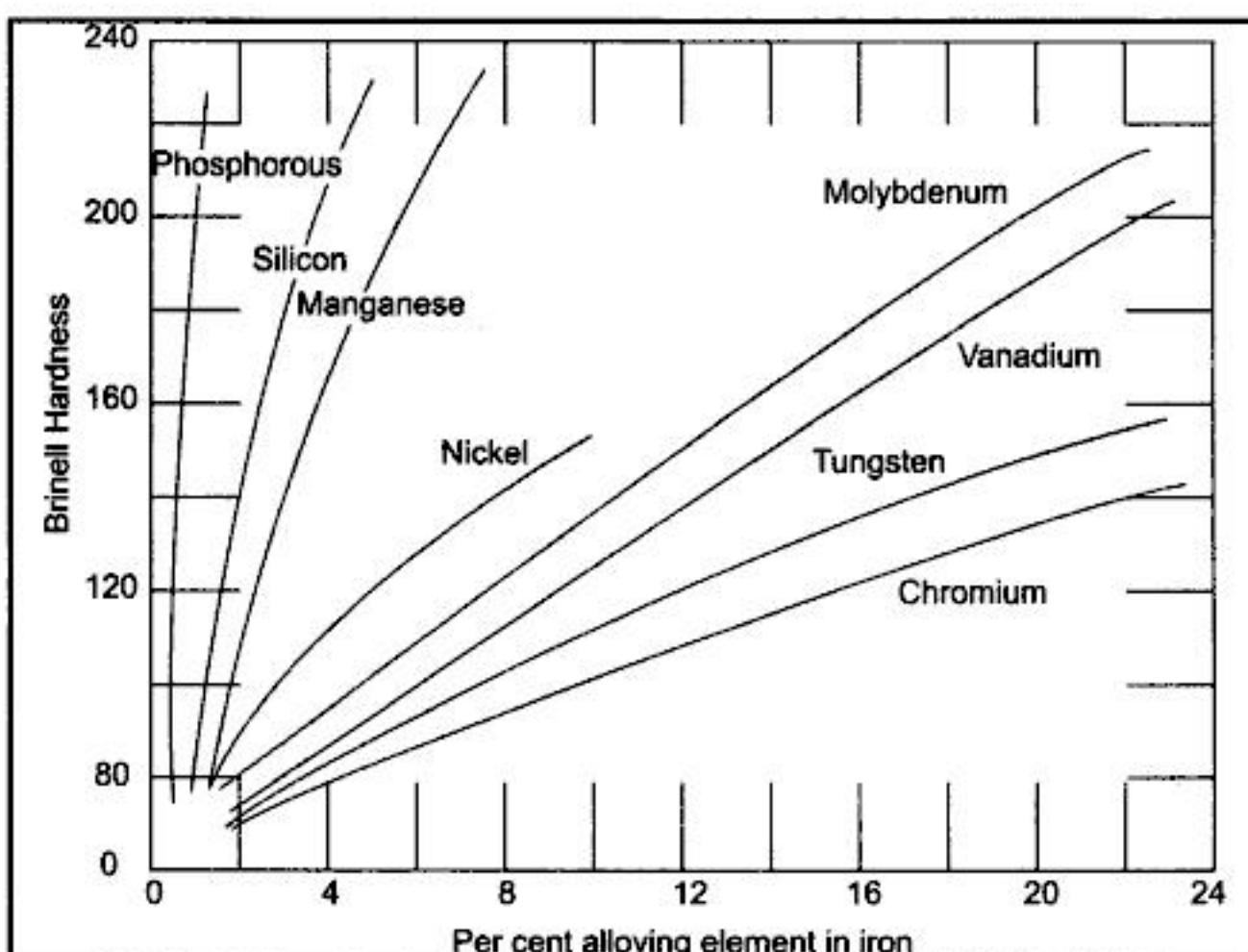


Fig. 2.12 Effect of alloying elements on the probable hardness of alloy steels

Tool steels would be designated by the letter T instead of C. For example, T103 is a tool steel with an average carbon percentage of 1.03 (0.95 to 1.10).

Alloy steels are designated by the chemical symbols of the significant elements followed by their percentages rounded up to the nearest whole number or if the percentage is less than one then the hundredths of a per cent with an underline.

For example, 35Mn2Mo45 represents the following average composition.

Carbon	0.35%
Manganese	2.00%
Molybdenum	0.45%

T35Cr5Mo1V30 is an alloy steel for making tools and has the following composition as per IS:3748-1966.

Carbon	0.30 to 0.40%
Chromium	4.75 to 5.25%
Molybdenum	1.20 to 1.60%
Vanadium	0.20 to 0.40%
Manganese	0.25 to 0.50%
Silicon	0.80 to 1.20%

American Specification This designation has been standardised by Society of Automobile Engineers (SAE) and American Iron and Steel Institute (AISI). A 2- or 3-digit number signifies the composition range of alloying elements followed by a 2 digit number referring to average carbon content in hundredths of a per cent. Some of the most generally used steels are as follows:

10XX	Plain carbon
13XX	Manganese 1.75
25XX	Nickel 5.0
31XX	Nickel 1.25; chromium 0.65
40XX	Molybdenum 0.25
41XX	Chromium 0.50 or 0.95; molybdenum 0.12 or 0.20
43XX	Nickel 1.80; chromium 0.50 or 0.80; molybdenum 0.25
44XX	Manganese 0.80; molybdenum 0.40
46XX	Nickel 1.85; molybdenum 0.25
51XX	Chromium 0.80, 0.88, 0.93, 0.95 or 1.00
61XX	Chromium 0.60, 0.80 or 0.95; vanadium 0.12 or 0.10 min or 0.15 min
81XX	Nickel 0.30; chromium 0.40; molybdenum 0.12
92XX	Manganese 0.85; silicon 2.00
93XX	Nickel 3.25; chromium 1.20; molybdenum 0.12

In the following tables comparative designations of steels which are used for manufacture are given.

Table 2.7 General steels with comparative standard designations

Usual description	IS Designation	British (1955) Designation	American Designation	German Designation
Mild steel	C20	En 3A	AISI 1020	C22
Medium carbon steel	C35	En 5	AISI 1035	C35
	C45	En 8D	AISI 1045	Ck45
	C55	En 9	AISI 1055	C55
	C60	En 43D	AISI 1060	C60
	C75	En 42	AISI 1078	C75
High-carbon steel	C100	En 44	AISI 1095	
Low alloy steel	40Cr90Mo15	En 19c	AISI 4142	42CrMo4
	40Ni2Cr1Mo25	En 24	AISI 4340	36CrNiMo4
	30Ni4Cr1	En 30A	—	35NiCr18
	55Si2Mn90	En 45	AISI 9260	
	50Cr1V23	En 47	AISI 6150	50CrV4
	17Mn1Cr95	En 207	AISI 5115	16MnCr5
	13Ni3Cr80	En 36	AISI 9310	14NiCr14
		En 111	AISI 3120	
		En 18A	AISI 5140	41Cr4

Table 2.8 Tool and die steels used for hot working

IS Designation	British (1971) Designation	American Designation
T33W9Cr3V38	BH21	H21
T35Cr5Mo1V30	BH11	H11
T35Cr5MoV1	BH13	H13
T35Cr5MoW1V30	BH12	H12
T55W14Cr3V45	BH26	H24

Table 2.9 Tool and die steels used for cold working

IS Designation	American Designation
T70Mn65	AISI A6
T118Cr45	AISI O5
T55Ni2Cr65Mo30	AISI A9
T105W2Cr60V25	AISI A5
T110W2Cr1	AISI A4
T90Mn2W50Cr45	ASTM O2
T55Cr70V15	AISI 6155

2.3**NON-FERROUS MATERIALS**

Ferrous materials are extensively used in the engineering industry because of their superiority, range of mechanical properties and lower costs. Still, non-ferrous materials are also used in various applications for their specific properties compared to ferrous alloys in spite of their generally high cost. Desired mechanical properties can be obtained in these alloys by work hardening, age hardening, etc., but not through normal heat treatment processes used for ferrous alloys. Some of the principal non-ferrous materials of interest are aluminium, copper, zinc, and magnesium.

2.3.1 Aluminium

Of all non-ferrous alloys, aluminium and its alloys are the most important because of their excellent properties. Some of the properties of pure aluminium for which it is used in the engineering industry are:

1. Excellent thermal conductivity (0.53 cal/cm/ $^{\circ}$ C)
2. Excellent electrical conductivity (376 600 /ohm/cm)
3. Low mass density (2.7 g/cm 3)
4. Low melting point (658 $^{\circ}$ C)
5. Excellent corrosion resistance. Aluminium, in fact, has greater affinity towards oxygen. As a result, when aluminium is exposed to air, the outer surface readily gets oxidized, forming aluminium oxide. This oxide skin has a good bond with the parent metal and thus protects it from further oxidation.

6. It is nontoxic.
7. It has one of the highest reflectivities (85 to 95%) and very low emissivity (4 to 5%).
8. It is very soft and ductile as a result of which it has very good manufacturing properties.

Some of the applications where pure aluminium is generally used are in electrical conductors, radiator fin materials, air conditioning units, optical and light reflectors, and foil and packaging materials.

In spite of the above useful applications, pure aluminium is not widely used because of the following problems:

1. It has low tensile strength (65 MPa) and hardness (20 BHN).
2. It is very difficult to weld or solder.

The mechanical properties of aluminium can be substantially improved by alloying. The principal alloying elements used are copper, manganese, silicon, nickel and zinc.

Aluminium and copper form the chemical compound CuAl₂. Above a temperature of 548°C it dissolves completely in liquid aluminium. When this is quenched and artificially aged (prolonged holding at 100–150°C), a hardened alloy is obtained. The CuAl₂, which is not aged does not have time to precipitate from the solid solution of aluminium and copper and thus is in an unstable position (super-saturated at room temperature). The ageing process precipitates very fine particles of CuAl₂, which causes the strengthening of the alloy. This process is called solution hardening.

The other alloying elements used are up to 7% magnesium, up to 1.5% manganese, up to 13% silicon, up to 2% nickel, up to 5% zinc and up to 1.5% iron. Besides these, titanium, chromium and columbium may also be added in small percentages. The composition of some typical aluminium alloys used in permanent moulding and die casting is given in Table 2.10 with their applications. The mechanical properties expected of these materials after they are cast using permanent moulds or pressure die casting is shown in Table 2.11.

2.3.2 Copper

Similar to aluminium, pure copper also finds wide application because of its following properties:

Table 2.11 Properties of cast aluminium alloys

Unified Aluminium association	Aluminium association	Hardness BHN	Ultimate ten- sile strength, MPa	Yield strength, MPa	Modulus of elasticity, GPa	Fatigue Strength, MPa
A03550	AA355.0	75.0 - 105	255	185	70.3	69.0
A03600	AA360.0	75.0	300	170	71.0	138.0
A03800	AA380.0	80.0	317	159	71.0	138.0
A03830	AA383.0	75.0	310	152	—	145.0
A03840	AA384.0	85.0	331	165	—	140.0
A03900	AA390.0	120.0	280	240	81.2	140.0
A04130	AA413.0	80.0	296	145	71.0	130.0
A04430	AA443.0	30.0 – 60.0	145	48.3	71.0	—
A05180	AA518.0	80	310	193	69.0	160.0

Table 2.10 Some aluminum alloys

Unified designation	Aluminum association	ASTM	Cu	Fe	Mg	Mn	Ni	Si	Zn	Applications
A03550	AA355.0	B26 (355.0)	1.0-1.5	0.6	0.4-0.6	0.5	Ti=0.25 Cr=0.25	4.5-5.5	0.35	Timing gears, impellers, aircraft and missile parts of high strength
A03600	AA360.0	B85 (360.0)	0.6	2	0.4-0.6	0.35	0.5	9.0-10.0	0.5	Improved corrosion resistance, superior strength
A03800	AA380.0	B85 (380.0)	3.0-4.0	2	0.1	0.5	0.5	7.5-9.5	3	Lawn mower housings, electronics chassis, engine components, home appliances, tools
A03830	AA383.0	B85 (383.0)	2.0-3.0	1.3	0.1	0.5	0.3	9.5-11.5	3	Intricate components
A03840	AA384.0	B85 (384.0)	3.0-4.5	1.3	0.1	0.5	0.5	10.5-12.0	3	Intricate components
A03900	AA390.0	SC174A) B85	4.0-5.0	1.3	0.45-0.65	0.1	Ti=0.2	16.0-18.0	0.1	Wear resistance
A04130	AA413.0	B26 (413.0)	0.6	2	0.1	0.35	0.5	11.0-13.0	0.5	Intricate details, excellent pressure tightness
A04430	AA443.0	B85 (443.0)	0.6	0.6	0.05	0.5	Ti=0.25 Cr=0.25	4.5-6.0	0.5	Greatest ductility
A05180	AA518.0	B85 (68A)	0.25	1.8	7.5-8.5	0.35	0.15	0.35	0.15	Used for marine and aircraft hardware

1. The electrical conductivity of pure copper is high (5.8×10^5 /ohm/cm) in its purest form. Any small impurity brings down the conductivity drastically. For example, 0.1% phosphorous reduces the conductivity by 40%.
2. It has a very high thermal conductivity (0.92 cal/cm/ $^{\circ}$ C).
3. It is a heavy metal (specific gravity 8.93).
4. It can readily be joined together by brazing.
5. It resists corrosion.
6. It has a pleasing colour.

Pure copper is used in the manufacture of electrical wire, bus bars, transmission cables, refrigerator tubing and piping.

The mechanical properties of copper in its purest state are not very good. It is soft and relatively weak. It can be alloyed profitably to improve the mechanical properties. The main alloying elements used are zinc, tin, lead and phosphorous.

The alloys of copper and zinc are called *brasses*. With a zinc content up to 39%, copper forms a single phase (α -phase) structure. Such alloys have high ductility. The colour of the alloy remains red up to a zinc content of 20%, but beyond that it becomes yellow. A second structural component called β -phase appears between 39 to 46 % of zinc. It is actually the inter-metallic compound CuZn which is responsible for the increased hardness. The strength of brass gets further increased when small amounts of manganese and nickel are added.

The alloys of copper with tin are called *bronzes*. The hardness and strength of bronze increase with an increase in tin content. The ductility is also reduced with the increase in tin percentage above 5. When aluminium is also added (4 to 11%), the resulting alloy is termed aluminium bronze, which has a considerably higher corrosion resistance. Bronzes are comparatively costly compared to brasses due to the presence of tin which is an expensive metal.

Some of the copper alloys with their compositions and applications are presented in Table 2.12.

Table 2.12 Some copper alloys

Alloy	Copper	Tin	Zinc	Others	Applications
Gun metal	88	10	2	—	Bearings, Bushes
Bronze	89	11	—	—	Bearings
Phosphor bronze	89.5	10	—	P = 0.5	Bearings, Springs
Bell bronze	75–80	20–25	—	—	Bells
Admiralty brass	70	1	29	—	Heat exchangers
Gilding metal	85	—	15	—	Coins
Naval brass	60	1	39	—	Marine applications
Cartridge brass	70	—	30	—	Deep drawing
Clock brass	58–60	—	38–40	Pb = 1.5–2.5	Clock parts and engravings
Aluminium brass	76	—	22	Al = 2	Marine applications

2.3.3 Other Materials

Zinc Zinc is principally used in engineering because of its low melting temperature (419.4°C) and higher corrosion resistance, which increases with the purity of zinc. The corrosion resistance is caused by the formation of a protective oxide coating on the surface. Principal applications of zinc are in galvanizing to protect steel from corrosion, in printing industry and for die casting.

The disadvantages of zinc are the strong anisotropy exhibited under deformed conditions, lack of dimensional stability under ageing conditions, a reduction in impact strength at lower temperatures and the susceptibility to inter-granular corrosion. It cannot be used for service above a temperature of 95°C because it will cause substantial reduction in tensile strength and hardness.

Its widespread use in diecastings is because it requires lower pressure, which results in higher die life compared to other diecasting alloys. Further, it has very good machinability. The finish obtained by zinc diecasting is often adequate to warrant any further processing, except for the removal of the flash present in the parting plane.

Magnesium Because of their light weight and good mechanical strength, magnesium alloys are used in applications where weight is important, for example, in aerospace industries and in applications involving very high speeds. For the same stiffness, magnesium alloys require only 37.2% of the weight of C25 steel, thus saving in weight. The two principal alloying elements used are aluminium and zinc. Magnesium alloys can be sandcast, permanent mould cast or diecast. The properties of sand-cast magnesium alloy components are comparable with those of the permanent mould cast or die-cast components. The die-casting alloys generally have high copper content so as to allow them to be made from the secondary metals to reduce costs. They are used for making automobile wheels, crank cases, etc. The higher the content, the higher the mechanical strength of magnesium-wrought alloys such as rolled and forged components. Magnesium alloys can be readily welded by most of the traditional welding processes. A very useful property of magnesium alloys is their high machinability. They only require about 15% of power for machining compared to low carbon steel.

2.4

HEAT TREATMENT OF METALS

Earlier, a detailed description of the iron–carbon equilibrium diagram has been presented, where all transformations that occur are under equilibrium conditions, allowing sufficient time for the reaction to take place. Therefore, time would never be represented in that diagram. By controlling the cooling rate, it is possible to alter the properties of steels. The process of affecting properties by controlled heating and cooling rates, is called *heat treatment*.

2.4.1 Transformation Curves

The basis for heat treatment is the time–temperature transformation curves or TTT curves where, in a single diagram, all the three parameters are plotted. Because of the shape of the curves, they are also sometimes called C-curves or S-curves.

To plot TTT curves, the particular steel is held at a given temperature and the structure is examined at pre-determined intervals to record the amount of transformation taken place. From Fig. 2.11, it is known that the eutectoid steel (C80) under equilibrium conditions contains, all austenite above 723°C , whereas below, it is

pearlite. To form pearlite, the carbon atoms should diffuse to form cementite. The diffusion being a rate process, would require sufficient time for complete transformation of austenite to pearlite. From different samples, it is possible to note the amount of the transformation taking place at any temperature. These points are then plotted on a graph with time and temperature as the axes. Through these points, transformation curves can be plotted as shown in Fig. 2.13 for eutectoid steel. The curve at extreme left represents the time required for the transformation of austenite to pearlite to start at any given temperature. Similarly, the extreme right curve represents the time required for completing the transformation. In between the two curves are the points representing partial transformation.

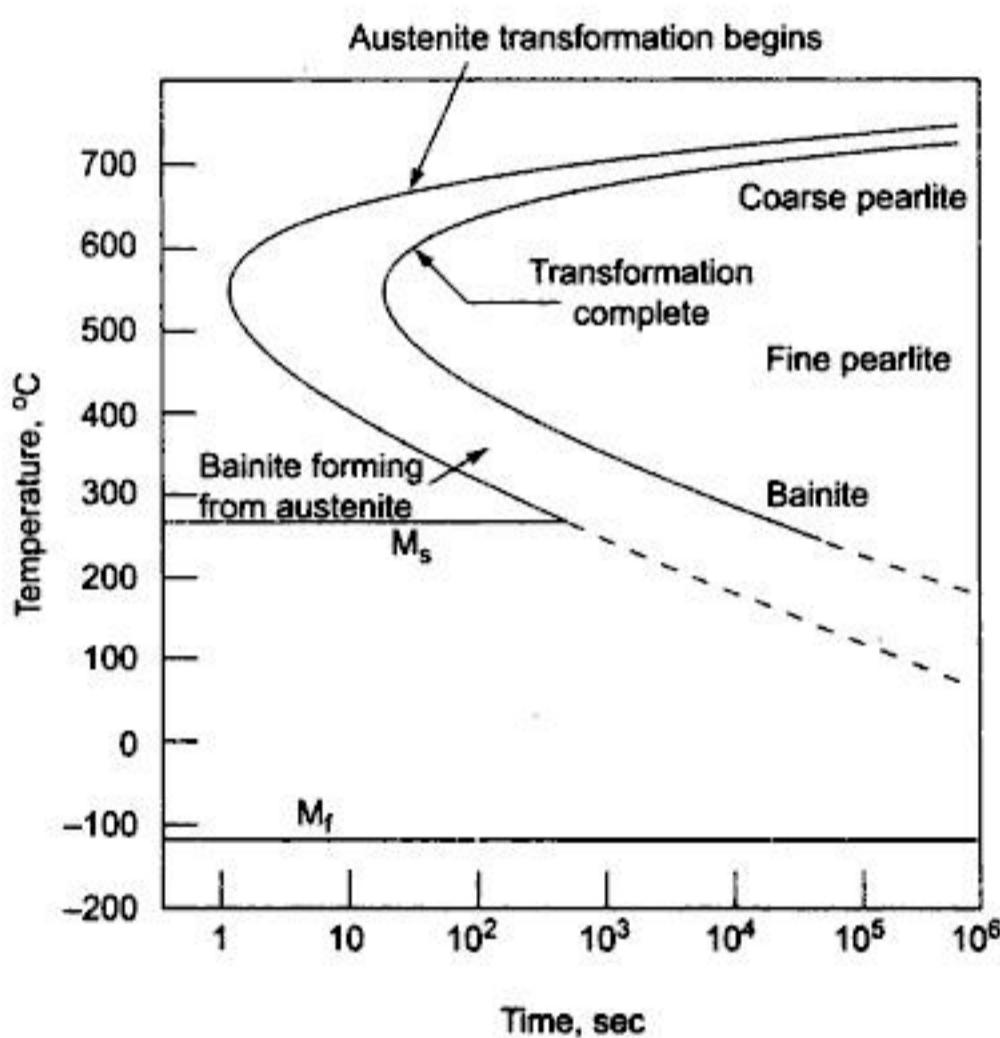


Fig. 2.13 Isothermal decomposition diagram of C80 steel

The horizontal lines M_s and M_f represent the start and finish of martensitic transformation. Since austenite needs time for transformation to pearlite, supercooled austenite would not have sufficient time for all of its carbon atoms to properly diffuse and form cementite. As a result, the carbon atoms would be trapped in the unit cell of iron. Since iron does not have enough interstitial space, the unit cell gets distorted with the extra carbon atoms. The distorted lattice structure is a body-centred tetragonal and is called *martensite*. The degree of distortion depends on the number of carbon atoms trapped in the cell. It is formed in steels when cooled rapidly at a high rate which is of the order of 500°C per second for plain carbon steels.

Martensite has a needle-like structure. It is extremely hard and brittle. As shown in Fig. 2.14, the maximum hardness of steel varies depending on the amount of carbon in steels. It is not possible to get any hardness in low carbon steels (less than 0.3% C). The maximum attainable hardness is reached by a carbon percentage of 0.7 to 0.8. The strength of martensite is derived from the fact that the movement of dislocations is effectively blocked by the distorted lattice.

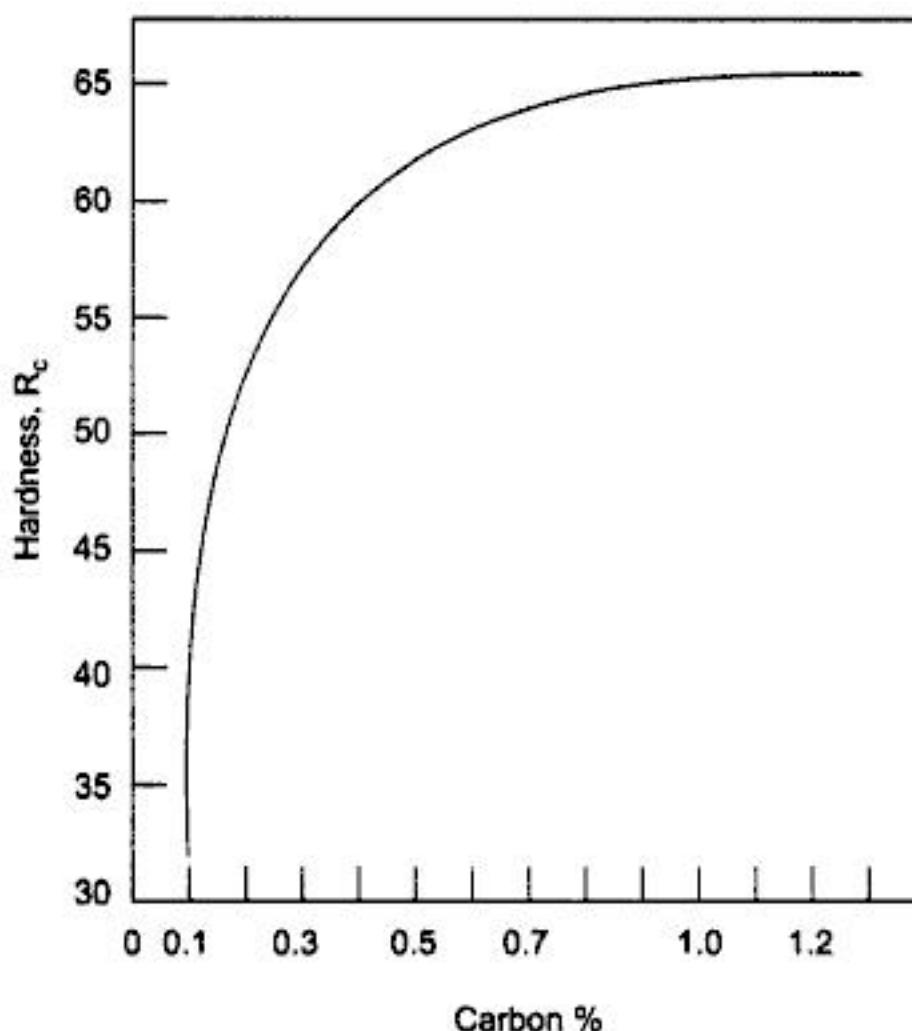


Fig. 2.14 Effect of carbon percentage on the hardness of martensite produced

Cooling rates employed to lower the austenitic temperature to room temperature control the final microstructure of steel. The final microstructure could be complete martensite, martensite with pearlite or complete

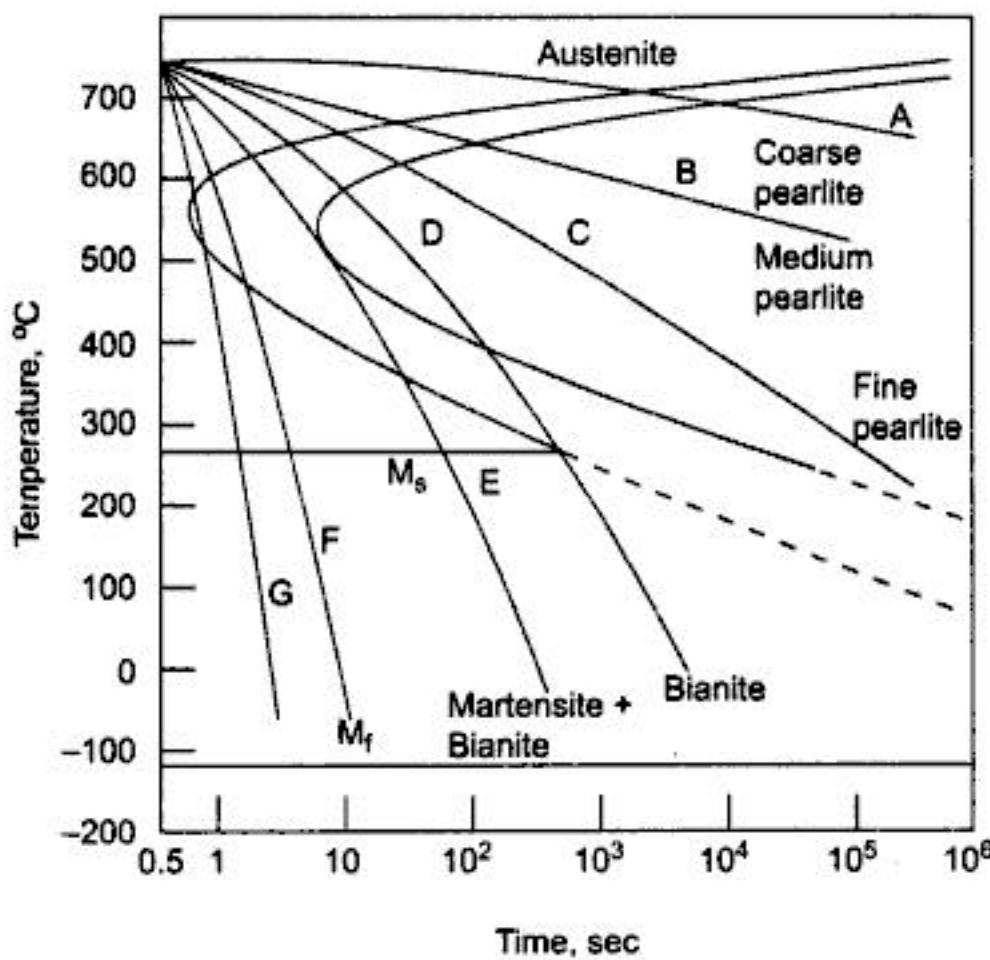


Fig. 2.15 Effect of cooling rates on the final structure of eutectoid (C80) steel

pearlite. Also, the final grain size of pearlite produced could vary from very fine to coarse, thus giving rise to wide varieties of properties that could be expected of them. Schematically, the cooling curves have been superimposed on the TTT curve in Fig. 2.15.

As seen from the TTT diagram, all the retained austenite may not be transformed unless the temperature reaches the M_f temperature. This is generally below the room temperature. The retained austenite (without transformation) can cause loss of strength or hardness, dimensional instability or cracking. In alloy steels since the alloying elements decrease the martensite transformation starting and ending temperatures, it may be necessary to cool the material to a lower temperature by the use of liquid nitrogen to get the full hardness.

The curve A represents extremely slow cooling rate which gives rise to conditions conducive to grain growth, thus producing very coarse grains of pearlite in steels. The curve B which shows faster cooling rate than A, would give rise to medium-sized pearlitic grains. Similarly, the curves C and D which represent faster rates than B but not so fast as to miss the complete transformation curve, produce complete pearlite which is extremely fine and called *bainite*. The bainitic structure is somewhat between pearlite and martensite. The cooling rates are faster in curves E, F and G than in the rest and thus not all the austenite is converted to pearlite. The retained austenite below the M_s line is all converted into martensite and thus, the final microstructure would be martensite and bainite. The amount of martensite formed increases as the cooling rate rises.

2.4.2 Hardening

To control the mechanical properties, it is essential to start with a structure of austenite since it is the state where the carbon atoms are distributed into the iron matrix uniformly. The austenitic structure in steels is achieved by heating it and soaking at a temperature above 723°C , depending on the carbon percentage. Typical temperatures used for various heat treatment processes of general steels is given Table 2.13. Relevant portion of the iron–carbon equilibrium diagram is presented in Fig. 2.16, with the temperatures marked for the various carbon compositions. Up to the eutectoid composition, complete austenite is achieved by heating above the line KL , but in hyper-eutectoid steels not all cementite is dissolved in austenite by heating just above the line KM (Fig. 2.16).

Hardening or quenching process involves first, bringing the steels into austenitic range by proper soaking at a temperature which depends on the thickness of the section. This steel is then rapidly cooled using any of the quenching media such as salt solution, water or oil. The heated material is directly dipped into the quenching bath as required for the particular steel. The critical cooling rate required for getting the complete martensitic structure in steels depends on the carbon percentage as shown in Fig. 2.17. Higher the carbon, lower is the cooling rate required.

Table 2.13 Comparative heat treatment temperatures for steels

Steel	Quenching, $^{\circ}\text{C}$	Normalizing, $^{\circ}\text{C}$	Annealing, $^{\circ}\text{C}$
C10 steel	900–925	900–955	540–730
C20 steel	870–910	900–955	540–730
C30 steel	855–900	870–915	675–745
C40 steel	815–855	855–900	845–885
C50 steel	800–845	845–900	830–870
C60 steel	790–845	830–885	815–855

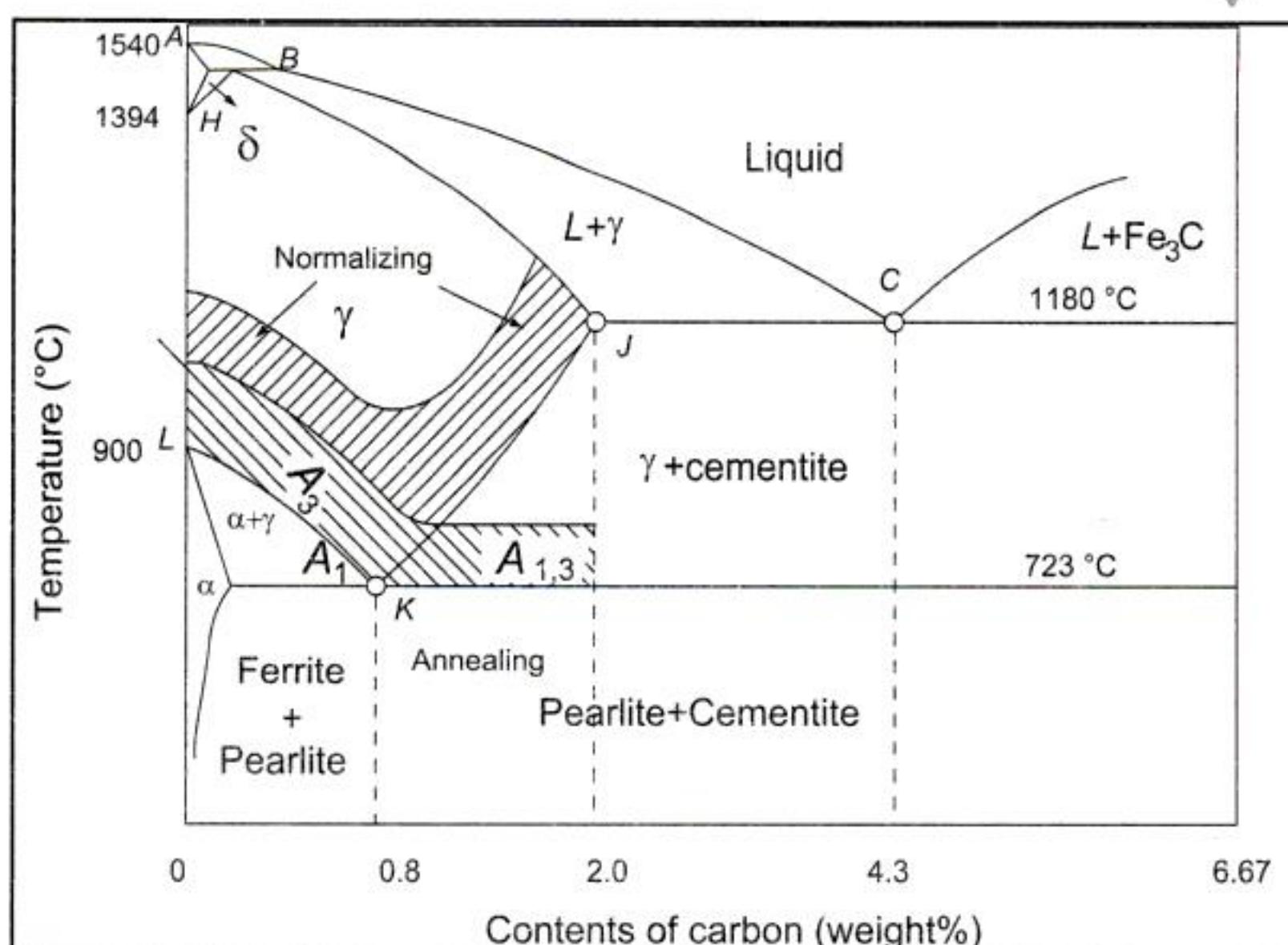


Fig. 2.16 Part of iron carbon equilibrium diagram relevant for heat treatment of steels

The quenching medium most generally used is water. This is because of its abundant availability, greater heat removal capabilities and low cost. Sometimes, salts may be added to water to increase the cooling rate. They are sodium chloride or sodium hydroxide. Because of the severity of cooling rate with salt baths, it is possible sometimes that distortions or cracks may appear in some components. Also, after quenching in salt baths, it is necessary to clean the components thoroughly to minimize the incidence of corrosion. Oils are also used as quenching media. They have lower cooling rate compared to water. But, the lower cooling rate cools steel more uniformly throughout thus reducing the risk of distortion. Also, quenching capacity of oils is not subjected to much change in the temperature range from 20 to 150°C. The oils are more suitable for high-carbon steels and alloy steels. The main disadvantage of oil is the flammability. Oils are more suitable as quenching media for low distortions. To get some residual stresses in the quenched parts, water is generally preferred. The comparative cooling rates with various cooling media are presented in Table 2.14.

Table 2.14 Comparative cooling rates

Brine	1.20 to 1.30
Water	1
Oil	0.40 to 0.50
Forced air	0.03
Still air	0.02

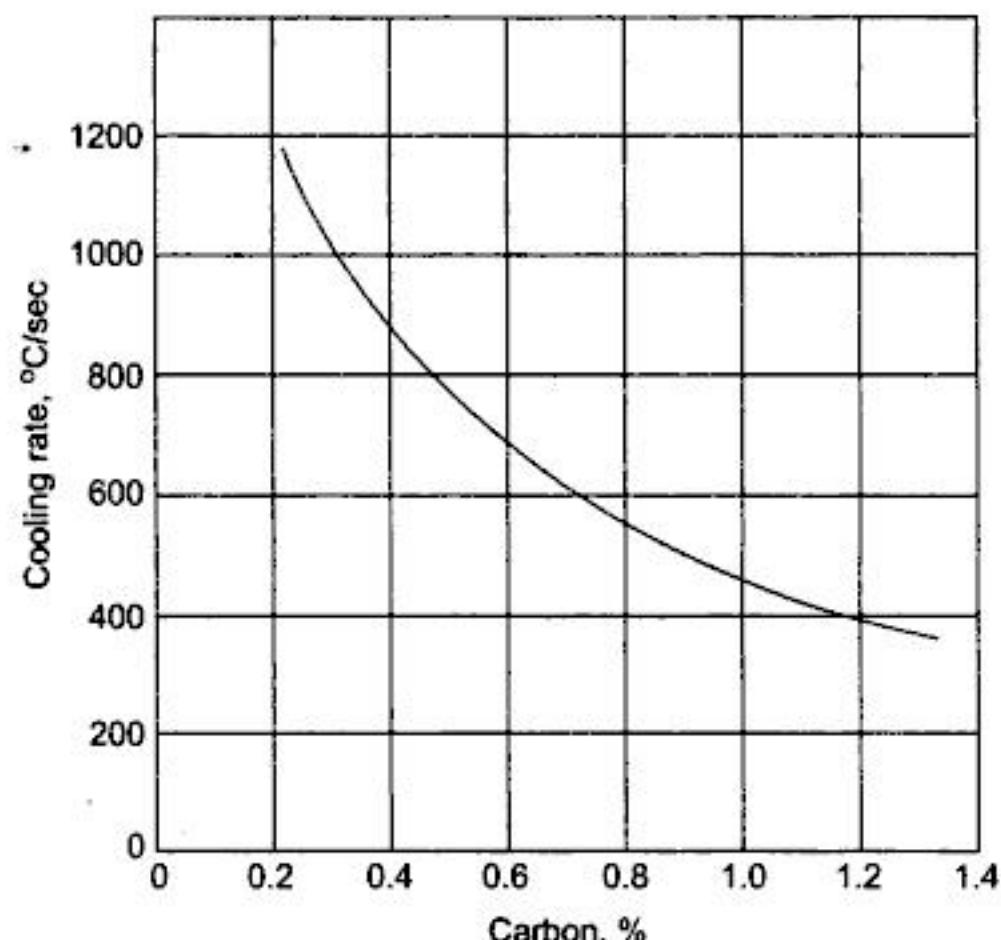


Fig. 2.17 Influence of carbon content on critical cooling rate for missing the transformation curve

The selection of quenching media is done based on a number of selection criteria.

- No excessive or unpredictable distortions
- No occurrence of cracks due to quenching
- To obtain the correct micro structure
- To produce the correct residual stress pattern

Hardenability and Jominy Test When thick sections are involved in the hardening process, the interiors would experience somewhat lower cooling rates due to slower heat transfer through steel than from the surface. As a result, the hardness of the material during quenching gradually changes as depth from the surface increases as shown in Fig. 2.18. The variation would be more for thick ones than the thin sections as shown for the 100-mm and 15-mm bars in Fig. 2.18. The depth and hardness achieved by quenching is called *hardenability*.

Hardenability should not be confused with hardness. Hardenability can be defined as the depth to which a certain hardness level can be obtained by the quenching process. High hardenability steel would be able to be thoroughly hardened without too severe a quenching rate. Under standard conditions, it is possible to determine the hardenability characteristics of different materials by *Jominy's end quench hardenability test*.

In this test, a standard test specimen (25.4 mm in diameter and 102 mm long) of the material, as shown in Fig. 2.19, is prepared. The test piece is heated to transform it into austenite completely and quenched by means of a water jet applied against the end of the specimen. Though the temperature of water and the flow rate is not critical to the hardness achieved, it is desirable to adhere to the standard condition as prescribed in the standards for the sake of comparison. When the specimen reaches the room temperature, a flat is ground to a depth of 0.4 mm on the side taking precaution that no grinding burn is caused. Hardness is measured

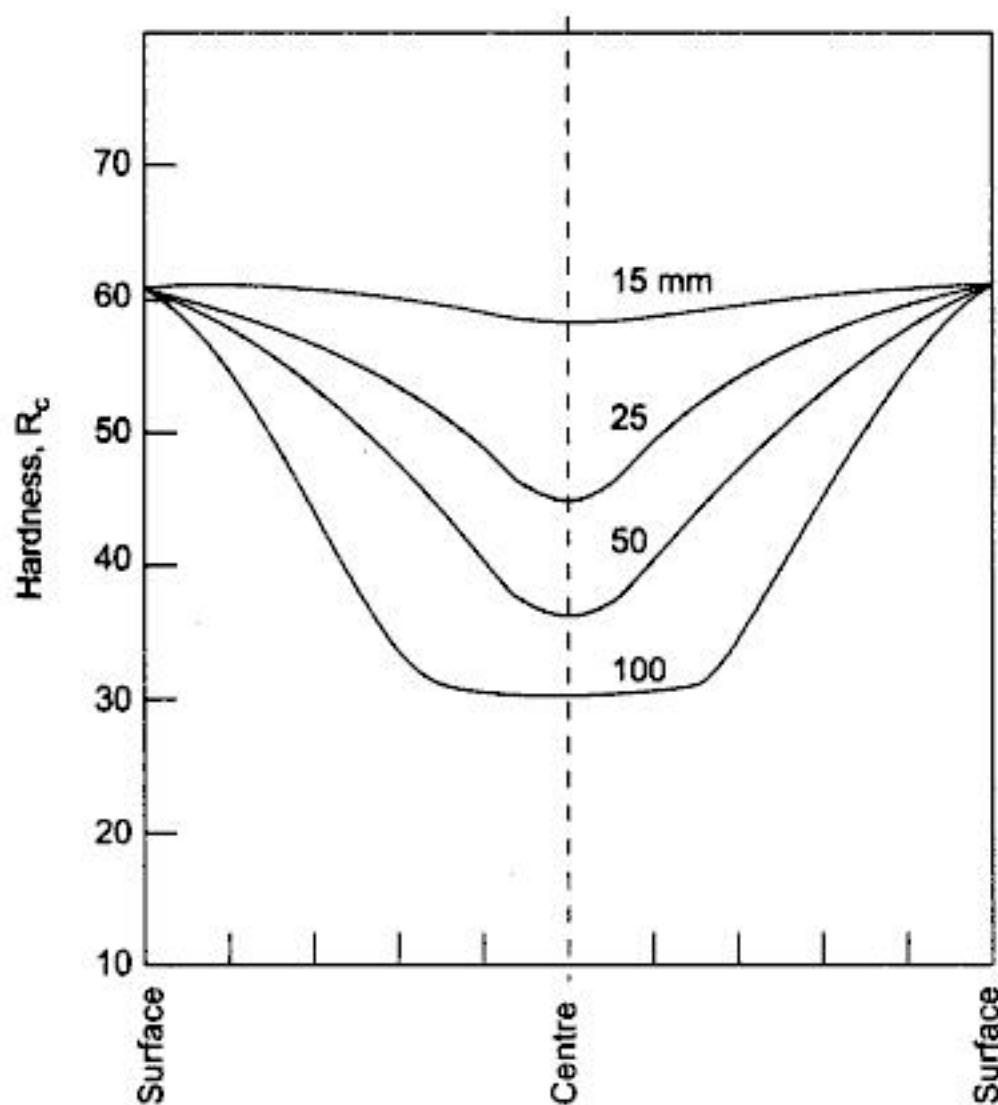


Fig. 2.18 Variation of hardness across the depth of C50 steel bar after quenching

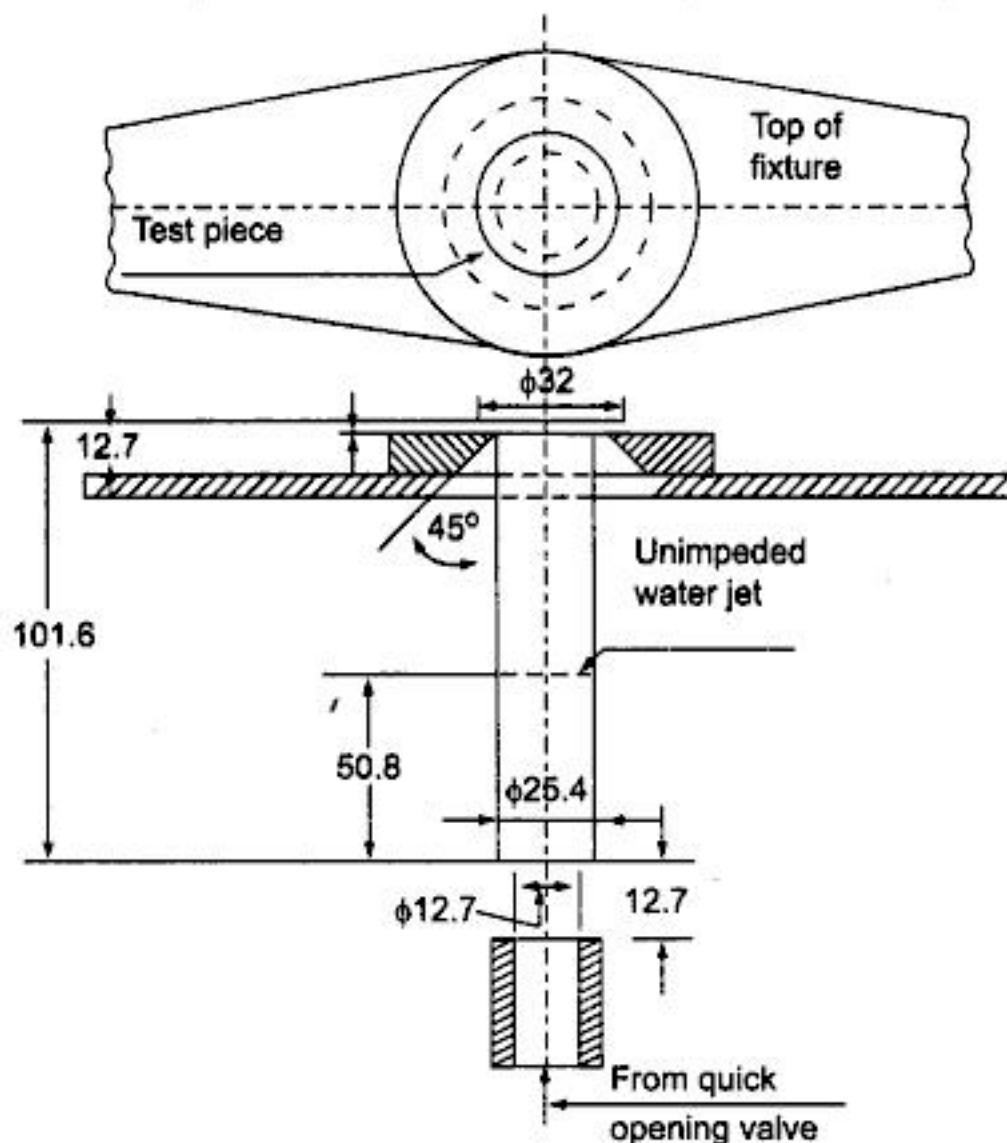


Fig. 2.19 Jominy's end quench hardenability test specimen

from the end using a micro-hardness tester, at regular intervals (1/16 inch or 1.5875 mm) which would give the hardenability characteristics of the material under consideration. This test is suitable for all steels except for those with very low or very high hardenability.

Typical values as found in a test specimen V-block for the effective cooling rates and the resultant hardnesses are shown in Table 2.15 below.

Table 2.15 Test data on hardenability on a test specimen

Location on V block	A	B	C	D
End quench bar distance in steps 1.5875 mm (1/16 inch)	1	4	4.8	12.1
Equivalent cooling rate (deg/s at 700°C)	272	69	47	9
Block hardness, Rc	56	45	37	27

2.4.3 Tempering

Martensite formed during the quenching process is extremely hard and brittle, and lacks toughness. Thus these steels are not suitable for some applications requiring impact resistance. Hence, a secondary heat treatment process called *tempering* is carried out on quenched steels, to achieve the necessary toughness and ductility by marginally sacrificing hardness. This process also relieves the internal stresses thus improving the ductility. Upon heating martensite during the tempering process, the resultant transformation leads towards an equilibrium state of the steel structure called *tempered martensite*. This is a structure where cementite is finely dispersed in the ferrite matrix.

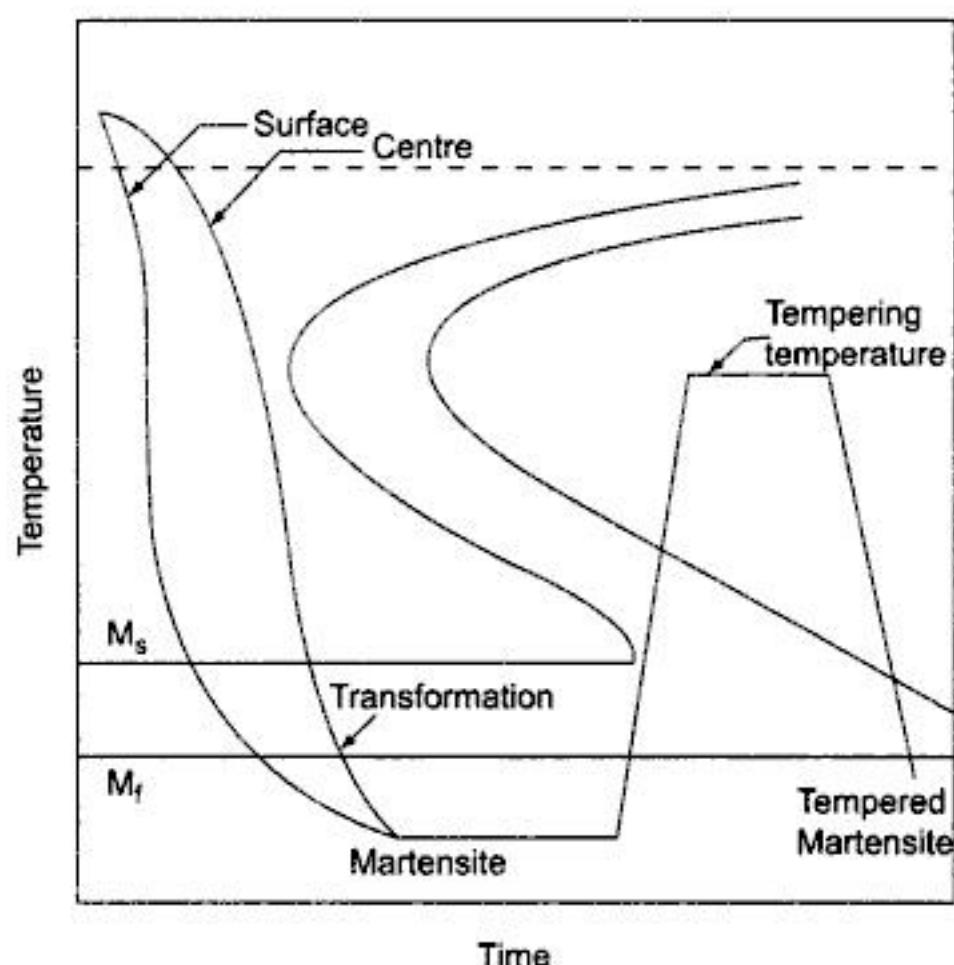


Fig. 2.20 Transformation diagram with cooling curve for tempering

The tempering procedure involves heating of quenched steel to a temperature from 200 to 400°C, holding it for a while and then cooling as shown in Fig. 2.20. Tempering is a one way process. If the hardness is to be regained, then the quenching process is to be repeated. The hardness of the steel finally achieved, depends on the tempering temperature used as in Fig. 2.21. The higher the tempering temperature, the lower would be the final hardness. In the case of alloy steels, many of the alloying elements have the tendency for reduction in hardness due to the tempering process particularly at low temperatures such as 200°C.

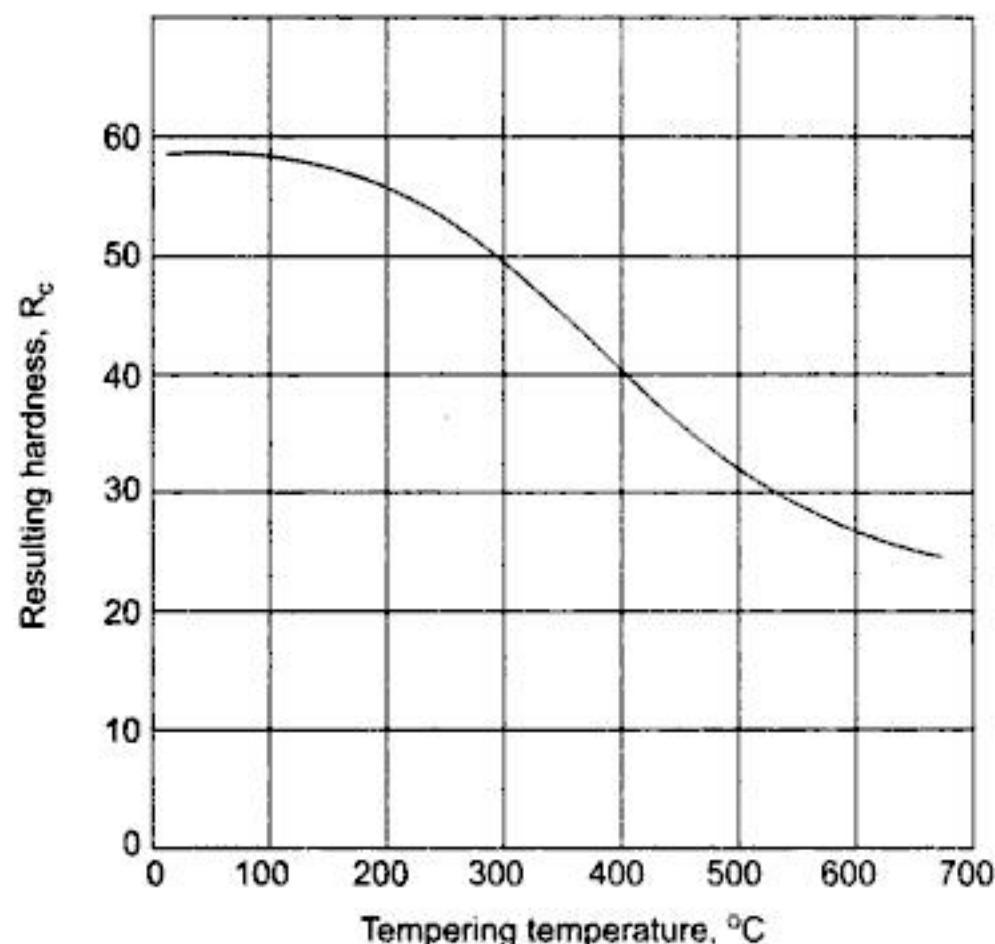


Fig. 2.21 Effect of tempering temperature on the resulting hardness of the plain carbon

Austempering The quenching process being severe, the martensite formed would be extremely crack-prone. A variation of the hardening process is austempering, wherein the material is quickly quenched a little above the Ms temperature to just miss the nose of the cooling curve, as shown in Fig. 2.22 and then maintained at the same temperature for a prolonged period so that austenite would be transformed to bainite (very fine pearlite) under isothermal conditions. This temperature is selected based on the desirable final hardness. The bainite formed is stress-free and likely to cause less crack formation in the material. This treatment is possible only for those steels which can be rapidly quenched without transformation. The properties obtained by austempering compare well with those of quenched and tempered steels, but with higher ductility and impact resistance as shown in Table 2.16. Though these results are for a C75 steel rod of 4.6 mm diameter, the application of austempering depends to a large degree on the isothermal transformation curve, the size of the workpieces and the final hardness desired.

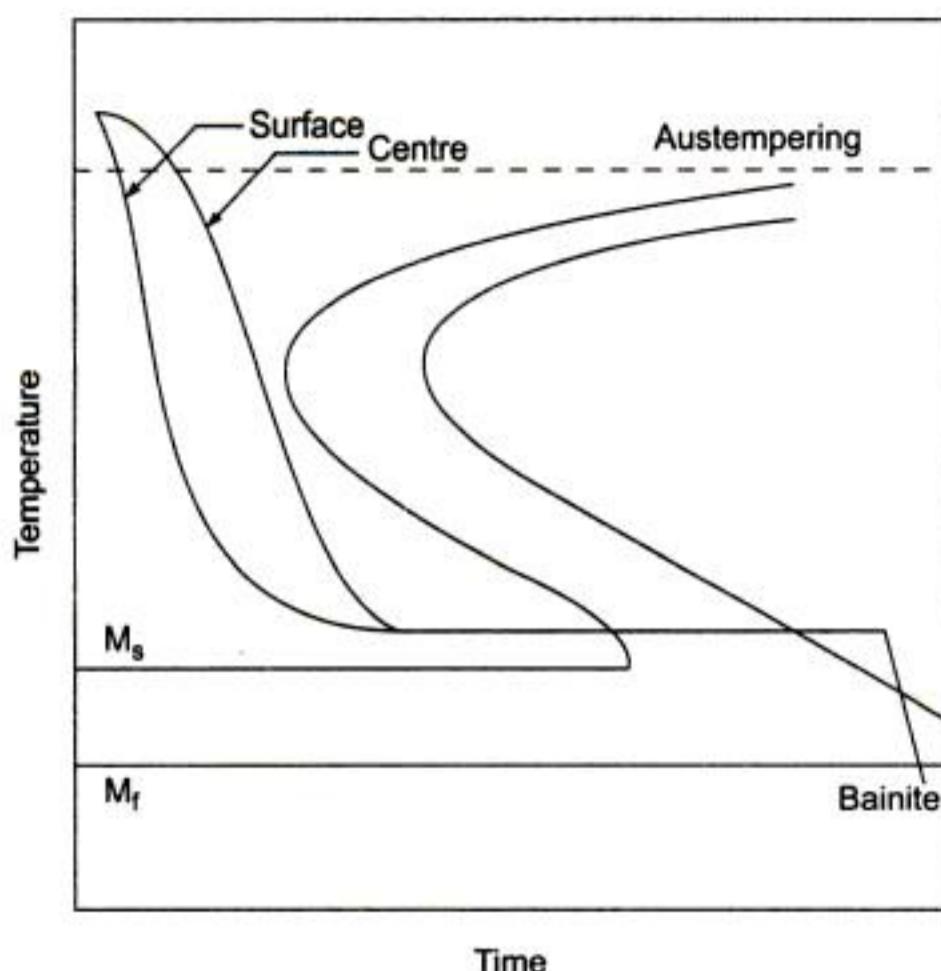


Fig. 2.22 Transformation diagram with cooling curve for austempering

Table 2.16 Comparison of final properties of steels with different heat treatment processes

	Austempered	Quenched and tempered
Hardness Rockwell C	50.4	50.2
Ultimate strength, MPa	1950.0	1700.0
Yield strength, MPa	1045.0	840.0
Elongation in 150 mm, %	1.9	0.3
Reduction in area, %	34.5	0.7
Impact energy, N m	47.9	4.0

Martempering In martempering, which is similar to austempering, the steel is heated to an austenitic range, followed by rapid quenching (water bath) to a temperature above the M_s temperature (Fig. 2.23). Thereafter, the material is maintained at constant temperature (oil bath) such that the entire section is brought to a uniform temperature. As soon as the workpiece attains uniform temperature, it is taken out of the bath and cooled in air. The air cooling is sufficiently fast such that martensite is formed. This provides relative stress-free material without any distortion and better mechanical properties compared to regular quenching and tempering process.

2.4.4 Annealing and Normalizing

Annealing is a widely used heat treatment process which involves heating the material to the austenitic temperature, and subsequently cooling it very slowly in a way similar to that of the cooling line A in Fig. 2.15. Such cooling rate is achieved by leaving the steel inside the heating furnace itself without any further heat input. Because of the extremely slow cooling rate, the final structure of the steel would be very coarse pearl-

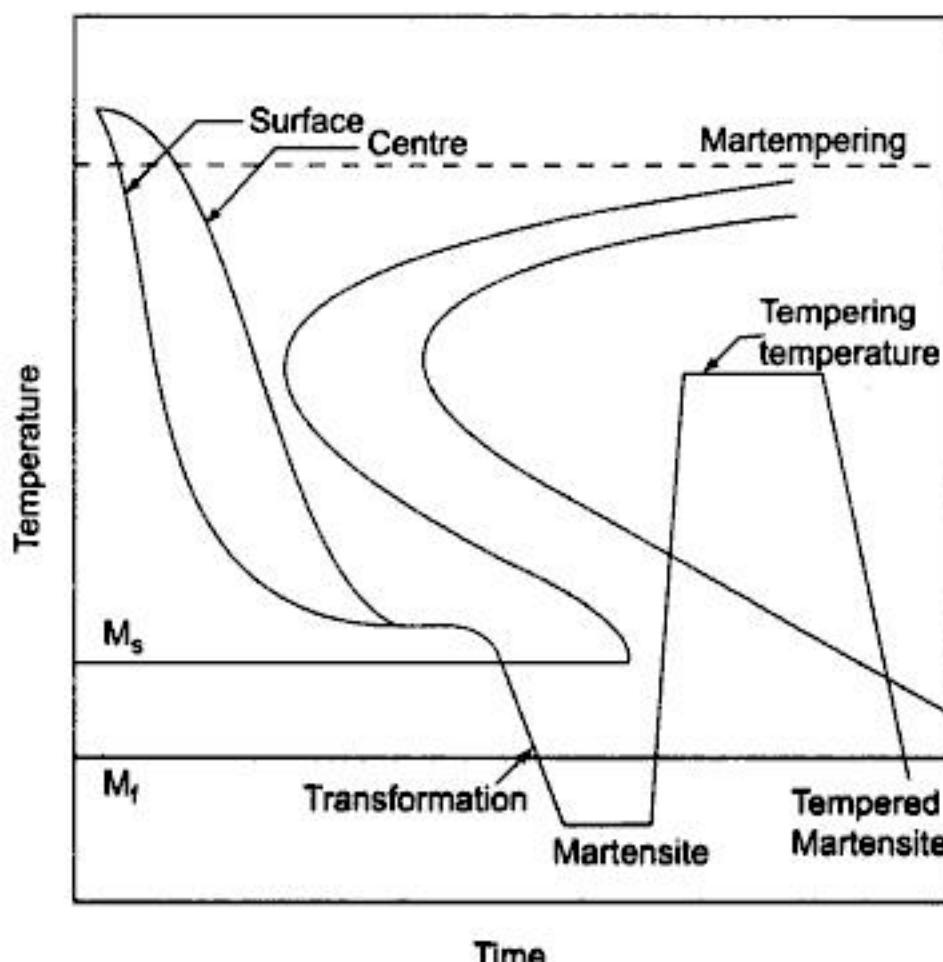


Fig. 2.23 Transformation diagram with cooling curve for martempering

ite. This structure would eliminate all internal stresses, reduce hardness, increase ductility, enhance machinability, refine grain size and also effect some changes in electrical and magnetic properties.

In normalizing, a somewhat faster cooling rate is used, as in curve C in Fig. 2.15. This may be achieved by cooling the heated specimen in still air. Because of the faster cooling rate, the pearlitic structure obtained would be of uniformly fine grain size. In the final structure there is better dispersion of cementite. This would result in higher tensile strength and hardness than what are possible by annealing. The mechanical properties achieved through normalizing depend to a great extent on the thickness of the section. In case of thicker objects or sections, the outer surface may be normalized, but the core would be annealed.

2.4.5 Case Hardening

Heat treatment processes covered so far are meant to be effective for the entire material, whereas case hardening processes are essentially meant for improving the hardness of the outer layers only, leaving the core to retain their original softness. In applications where it is desired to have greater hardness on the surface to take care of the abrasive forces, and a soft core to provide the necessary toughness for absorbing any impact forces, case hardening would generally be ideal.

Case Carburizing This is carried out for low-carbon steels which do not respond readily to quenching process because of the very low carbon content. In this process, the specimen along with a carbonaceous material such as charcoal, is packed in a sealed container and kept in a furnace. The pack is heated to a temperature between 800 to 950°C and held for a period of 4 to 20 hours. On heating, the oxygen present in a small amount in the sealed container reacts with the charcoal and forms carbon monoxide (CO). The carbon monoxide upon coming in contact with the specimen, releases oxygen while the carbon diffuses into the outer skin of the specimen. The released oxygen will again form CO with charcoal and the whole process gets

repeated. As the time continues, sufficient amount of carbon gets into the material resulting in a medium- to high-carbon steel in the skin of the specimen.

The amount of carbon diffused into steel depends on the carburizing temperature and time. The case depth achieved with carburizing time is shown in Fig. 2.24. The carburising rate is initially high, but as time progresses, the rate decreases slightly. The case depth achieved is generally between 1 to 2 mm. Also, the carbon content varies with very high amounts on the surface but decreasing gradually as depth increases. The process is called pack carburizing, since the specimen is packed with charcoal or any other carbonaceous material. The case depth achieved is a function of the quality of the coal and as such there is little uncertainty.

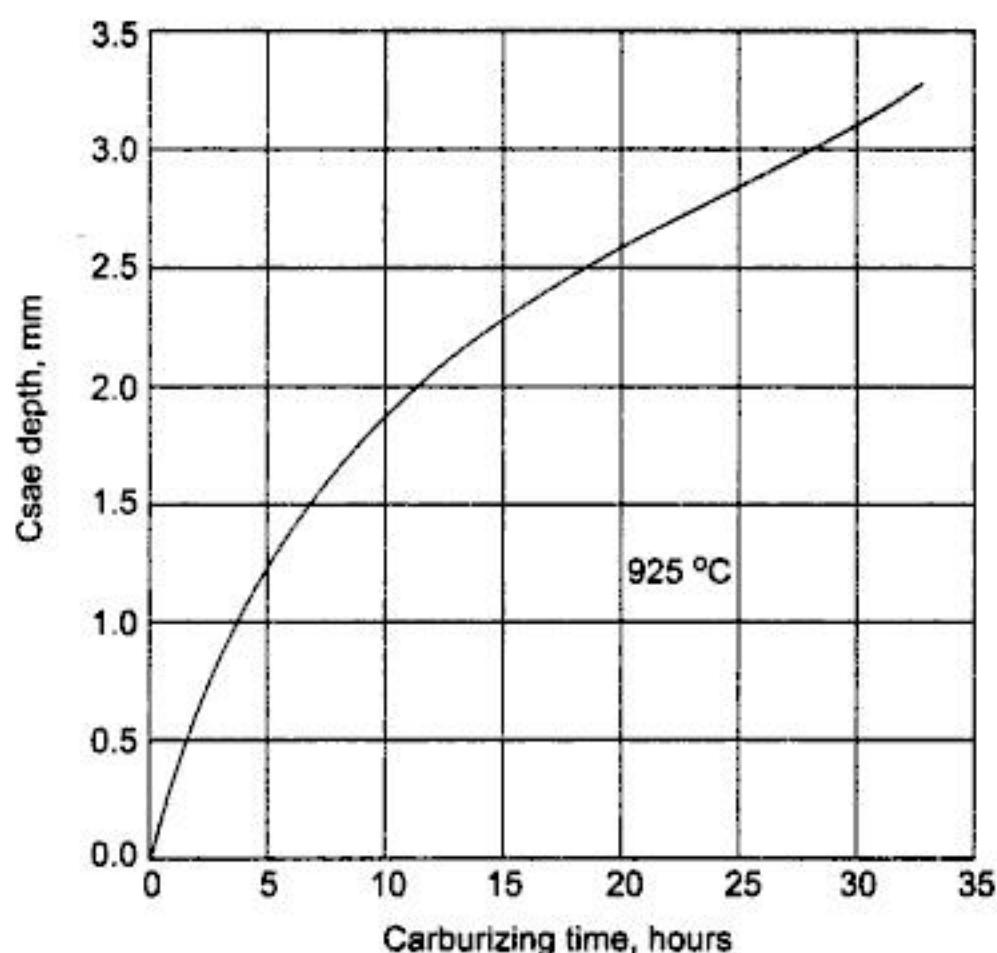


Fig 2.24 Effect of pack carburizing on the case depth produced in 15Ni1Cr65

The other type which is more generally used is the gas carburizing, where carbon in gaseous form such as natural gas, propane or methane is used instead of charcoal. The process is very similar to pack carburizing. The main advantage of gas carburizing is to have the better control of surface carbon and case depth than that is possible in pack carburizing.

In case carburizing grain size may be affected because of the prolonged heating. The case carburised steel is to be further hardened by a secondary heat treatment process of quenching and tempering depending on the desired application. Some normalization may also be done to refine the grain structure.

The characteristics of the process are the following:

- Hard and highly wear resistant surface (medium case depths)
- Excellent capacity for contact load
- Good bending fatigue strength
- Good resistance to seizure

- Excellent freedom from quench cracks
- High capital investment

Cyaniding Also called *liquid carbonitriding*, the cyaniding process involves addition of carbon and nitrogen to the cases of carbon steels and alloy steels. This is achieved by heating the steel in contact with a molten bath of cyanide. The cyanide bath may consist of sodium cyanide, potassium cyanide, or potassium ferro-cyanide with inert salts such as sodium chloride and sodium carbonate which provide the necessary fluidity to the cyanide bath. The bath is maintained at a temperature from 750 to 850°C and the contact time is between 30 and 60 minutes. This produces a reasonable case depth of nearly 0.15 mm. The longer contact times can produce a larger case depth. In view of the large heat transfer coefficient of the liquid bath, the distortion of the workpiece is minimized. After the cyaniding process, the steel is quenched either in oil or water-based quenching medium to produce the desired case hardness. If necessary, it may be followed with a low temperature tempering.

The process is faster than the carburizing process, but achieves shallow case depths. It is generally employed for parts that do not require finishing after hardening. This process is not suitable for parts requiring high impact resistance since nitrogen addition is detrimental for these properties.

The characteristics of the process are the following:

- Hard and highly wear resistant surface (shallow and uniform case depths)
- Fair capacity for contact load (even at relatively high operating temperatures)
- Good bending fatigue strength
- Good resistance to seizure
- Good dimensional control possible
- Excellent freedom from quench cracks
- Medium capital investment

Nitriding Alloying elements in steels such as aluminium, chromium, vanadium and molybdenum would form very hard nitrides when they come in contact with nitrogen. This is made use of in the process of nitriding where alloy steels are case hardened without any quenching process. The nitriding temperatures are in the range of 500 to 575°C. The steels which are already quenched and tempered are put in a sealed container with ammonia gas and then heated to the nitriding temperature. The process is maintained for a duration of 8 to 40 hours (as high as 125 hours in some cases) for getting the necessary case depths. The nitrogen forms complex nitrides with the alloying elements, whose depth depends on the nitriding time.

Because of the lower temperatures employed in nitriding, there are less possibilities of distortion and deformation than any other case hardening process. Also, this process increases the wear resistance and fatigue life greatly. Further, no finish machining is required.

The characteristics of the process are the following:

- Hard and highly wear resistant surface (shallow case depths)
- Fair capacity for contact load
- Good bending fatigue strength
- Excellent resistance to seizure
- Excellent dimensional control possible
- Excellent freedom from quench cracks
- Medium capital investment

Flame Hardening This is the simplest form of heat treatment process. The workpiece is heated by means of a gas torch (oxyacetylene flame) followed by a water spray on the heated parts. The heat from the torch penetrates only to a small depth on the surface and consequently the steel in the outer layers gets quenched to martensite and bainite. Case depths up to 3 mm can be achieved by this process. This process can be followed by heating to about 200°C for the purpose of stress relieving. The surface hardness is not appreciably affected by this reheating operation. This process is suitable for any complex shape of the component such as crank shaft, large gears, cams, etc., with carbon percentages ranging from 0.3 to 0.6%. Though high-carbon steels can also be flame hardened but greater care is needed to avoid surface cracking.

The characteristics of the process are the following:

- Hard and highly wear-resistant surface (deep case depths)
- Good capacity for contact load
- Good bending fatigue strength
- Fair resistance to seizure
- Fair dimensional control possible
- Fair freedom from quench cracks
- Medium capital investment

Induction Hardening This is similar to the flame-hardening process where the heating of the component surface is achieved by the electromagnetic induction. The workpiece such as crank shaft is enclosed in the magnetic field of an alternating (10 kHz to 2 MHz) current conductor to obtain case depths of the order of 0.25 to 1.5 mm. This causes induction heating of the workpiece. The heated workpiece is then quenched by water spray. The induction heat penetrates only the outer surface of the workpiece and as a result, only the skin gets hardened by the quenching process. The whole process is very fast (5 seconds to 4 minutes) and results in hard outer surface (50 to 60 Rc) which is wear resistant.

2.4.6 Laser Heat Treatment

Hardening of ferrous alloy surfaces using laser radiation relies on the ability of the surface to get austenitized, and then get transformed to martensite/bainite/pearlite depending upon the associated cooling rate achieved. A laser beam is scanned across the component that causes the surface to heat rapidly. The surrounding material acts as an efficient heat sink, leading to rapid quenching and hardening phase transformations. As a result, a hardened surface layer is produced, while the desirable bulk properties, such as toughness and ductility, remain unaffected throughout the material. Components made from hardenable ferrous alloys are particularly suitable for laser hardening. Depending on the material, hardness values up to about 1,000 HV can be achieved to a depth of around 1.5 mm through solid-state transformation without surface melting.

During the process of laser heat treatment, the base material microstructure (generally pearlite and ferrite in as-received condition) will be transformed to austenite by the laser heating process. Subsequently, the heat from the processing zone is removed by the bulk of the material through heat conduction, providing sufficient cooling rate for the metallurgical transformations that lead to the martensitic and bainite formation, thus improving the hardness.

In order for the laser heat treatment to be successful, the following conditions should be satisfied:

- Temperature for the zone being hardened should reach well into the austenitizing zone.
- Between heating and cooling cycles, the substrate should be maintained at the austenitizing temperature long enough for carbon diffusion.

- There should be enough mass so that the cooling rate by self-quenching is such that it could satisfy the critical quenching rate requirement.

Laser heat treatment process is applied to a variety of components and is credited with the successes that are not possible with other heat treatment processes. A number of benefits have been claimed for the laser heat treatment process. Some of the advantages are the following:

- High processing speeds since laser radiation will not have any inertia. This allows for rapid starting and stopping, as well as high production rates. This provides great flexibility in the operation.
- Improved surface hardness, strength, lubrication, wear and fatigue properties.
- Surface hardening can be achieved with little or no contamination (i.e., without using chemicals such as fuels and cooling media), allowing for very minimal environmental impact.
- No separate quenching is required, since the mass of the part acts as a heat sink with sufficient cooling rate. Some small parts may require quenching with an external medium.
- It is possible to obtain higher case hardness compared to the conventional case hardening processes.
- Can be even applied to the lower carbon steel because of extremely rapid cooling rate that can be achieved by laser heat treatment.
- Greater product design flexibility with respect to material selection and geometry.
- Selective hardening of localized workpiece surfaces. Here, a selective hard surface arises with a tough centre and uninfluenced areas in the direct neighbourhood.
- Special geometries such as hardening tracks at cutting edges, guide tracks, grooves and free mould surfaces with continuous crossing geometry can be easily hardened using laser.
- It is possible to achieve good hardening of surfaces that are difficult to reach such as craned grooves, flutes, inside fillets and interior surfaces.
- It is also possible to dot harden at naps and in blind holes.
- Hardening can be done for some thin, warp-prone parts by a selective, quick heat input at an extremely short dwell time.
- Use of a few hardened tracks or paths instead of a fully hardened surface.
- Greater flexibility and precise localization of the hardened area making use of computer controlled operation for the positioning of the workpiece surface. It is possible to automate the process so that it can be integrated into machining cells.
- Greater precision and lower energy input, leading to reduced post-treatment work. The distortion of the components due to laser heating will be very low.

Limitations to the Process There are certain limitations of the process, which need to be well understood and taken care of in the process and product design.

- The metallic surfaces generally have reflectivity, which does not allow all the laser power to be absorbed. To overcome this difficulty, the surface needs to be painted black (or pickled) so that as much of laser energy as possible can be absorbed. This means that the produced component has to be cleaned and dried, before the paint can be applied. This calls for additional operations and cost. Also, after the operation, the leftover residue of the black paint needs to be cleaned.
- Laser hardening process is suitable for single-pass operation for a finite surface. However, if a large surface is to be hardened, then the laser beam has to traverse the entire surface in a suitable manner to completely cover it. One possibility is to have a helical path for a cylindrical surface. During this process, there is a possibility of some overlap heating of the surfaces by the laser, which will temper part

of the surface. This may produce some soft spots in an otherwise hard surface produced. It needs to be established whether such soft areas are useful for the operation or detrimental.

- Suitable only for steel and cast iron that are heat treatable.
- Parts without sufficient mass may heat up (ahead of the beam) thus curtailing self-quenching, and therefore, may require a separate quenching operation.
- Alloys that require higher soaking times for austenitization, such as steels containing stable spheroidal carbides and ferritic cast irons are not suitable for laser heat treatment.
- The depth of the hardness produced is very small and generally limited to about a few millimetres.

Laser hardening has been used since the early 1970's for hardening components, particularly in the automotive and machine tool industries. Camshaft lobes, axle bearings, ratchets, cylinder liners, blanking dies, piston rings, gear housings, gear teeth and valve guides are typical examples. In general, if the surface area to be hardened is less than 10% of the total surface area of the component, and the material can be hardened through thermally-induced phase transformations, then laser hardening is often the most economic hardening process.

2.4.7 Heat Treatment of Non-Ferrous Alloys

One of the principal mechanisms by which the non-ferrous alloys are heat treated is precipitation hardening. In this process, a second phase of the alloy is dispersed finely in the matrix of the first phase in solid state thereby increasing the strength. The inter-metallic compound present in a solid solution is generally hard and its presence increases the hardness even in a single-phase alloy. For example, a copper alloy with zinc forming the alpha solid solution, the hardness increases by about 39% when the zinc percentage is increased from 0 to 30%.

In precipitation hardening, the alloy is heated and soaked to form a single-phase solid solution. This then is cooled quickly (e.g., quenched in water) so that the single-phase structure is retained even at the room temperature. When this material is heated to a certain temperature and retained at that temperature for specified periods, then the precipitation of the second phase at a number of random locations throughout the solid solution takes place, thus increasing the strength of the alloy.

The hardness obtained is a function of precipitation temperature since the size of the precipitating particles and their distribution controls the movement of dislocations. If the particles are too coarse, then they are too dispersed and will not give rise to high strength. Hence it is important to know the temperature and time to get an optimum size of the particles and their distribution so that best strength can be obtained by the precipitation hardening process. If the precipitation process occurs at the room temperature, it is called *age hardening*.

Summary

Knowledge of the properties of engineering materials is an essential requirement in understanding the various manufacturing processes and their behaviour.

- There are a number of properties of engineering materials such as strength, ductility, hardness, and toughness that are important from the application point of view.
- There are specified tests for each of these properties that provide standardized methods for measurement and understanding their relevance.
- Iron alloyed with carbon plays an important role in providing a large range of properties suitable for different engineering applications. Properties of steels (alloys of iron and carbon) depend on the amount of carbon present as well as the microstructure of the compounds formed by iron and carbon.
- Addition of different alloying elements to steels enhances special class of properties for specific applications, thereby extending the functionality of plain carbon steels.

- Aluminium and copper are the two most widely used non-ferrous materials used in engineering industries. Their properties can be manipulated by the addition of alloying elements similar to steels. In addition, there are other non-ferrous alloys which are being used for specific applications.
- Specialized heat treatment processes help in improving the properties of ferrous and non-ferrous alloys to suit the specific applications. Quenching is the process used for medium and high-carbon steels to improve the hardness by heating above the austenitic range followed by the sudden cooling. Other heat treatment methods reduce the internal stresses, and improve ductility. Other class of heat treatment processes increase the surface hardness while retaining the softness of the core.



Questions

- 2.1 Define strength. Explain the procedure for measuring the tensile strength of steels.
- 2.2 Explain the behaviour of steels when they are tensile loaded.
- 2.3 Define the following as related to engineering materials and explain the principles of their measurement.
 - a) Hardness; b) Ductility.
- 2.4 Briefly explain the Brinell hardness test.
- 2.5 Explain how the toughness of a material is measured.
- 2.6 What are the different tests available for hardness measurement? Compare their individual merits.
- 2.7 Describe the Izod impact test.
- 2.8 Compare the different methods available for measuring impact resistance of engineering materials.
- 2.9 Compare the properties of hardness and toughness from the application engineering point of view. Mention how one may choose these properties for a given application.
- 2.10 State the difference between steel and cast iron, with respect to their compositions.
- 2.11 State the reason why white cast iron is more brittle than grey cast iron.
- 2.12 State how carbon content influences the strength and ductility of plain carbon steels.
- 2.13 State how the properties of alloy steels are affected by the following alloying elements: manganese, chromium, and tungsten.
- 2.14 Name two alloying elements other than carbon, commonly employed in steel and state how they influence the properties of steel.
- 2.15 State the composition and application of an alloy steel.
- 2.16 State the ranges of composition for low-, medium- and high-carbon steels. Give two applications for each range.
- 2.17 Make a classification of the commonly used engineering materials. Insert the following materials under appropriate heads: grey cast iron, brass, duralumin, stainless steel, nylon.
- 2.18 Differentiate between steel and cast iron with reference to their carbon percentage, tensile strength, hardness and toughness.
- 2.19 State the composition and applications of two of the following: low carbon steel, duralumin, yellow brass.
- 2.20 What do you understand by the term 'steel'? Explain the effect of each of the alloying elements present in an alloy steel.
- 2.21 State along with an example how the Indian standard designation for structural steels is specified.
- 2.22 Write the composition of the following steels:
 - 25 Mn 1 S 14
 - 55 Si 2 Mn 90
 - 50 Cr 1 V 23
 - 40 Ni 2 Cr 1 Mo 25

T 105 Cr 1 Mn 60
T 75 W 18 Cr 4 V 1
15 Mn 75
55 Mn 1
35 Mn 2 Mo 45
31 Ni 3 Cr 65 Mo 55
T 50 W 2 Cr 1 V 18
16 Ni Cr 2 Mo 20

- 2.23 List any two commonly used nonferrous alloys stating their composition and application.
- 2.24 State the advantages of aluminium alloys over ferrous alloys.
- 2.25 Give the composition of two copper-based alloys and their applications.
- 2.26 What is meant by solution hardening?
- 2.27 What is the effect of copper as an alloying element in aluminium alloys? Explain.
- 2.28 What are the specific advantages of copper which make it a good engineering material compared to steel?
- 2.29 Describe briefly about brasses.
- 2.30 Write a short note on bronzes.
- 2.31 Give the composition of any two aluminium alloys with applications.
- 2.32 Distinguish between the following:
a) Quenching and tempering
b) Normalizing and annealing
c) Cementite and martensite
- 2.33 Why don't low-carbon steels respond to hardening by quenching process?
- 2.34 Distinguish clearly between hardness and hardenability. Explain a method of measuring the hardenability of steel.
- 2.35 Explain why tempering follows the quenching process in the heat treatment of steels.
- 2.36 Differentiate between normalizing and annealing in terms of the process and nature of the product.
- 2.37 Why is annealing done?
- 2.38 State the purpose served by quenching and tempering.
- 2.39 What are the case hardening processes that are normally used?
- 2.40 Is case carburizing done to high-carbon steels? State reasons supporting your answer.
- 2.41 Briefly explain the process and application of the following:
a) Case hardening b) Annealing
- 2.42 Briefly describe the following processes:
a) Carburizing b) Nitriding
- 2.43 Explain briefly what you understand about TTT curves.
- 2.44 Explain the necessity of heat treatment for steels. Describe the process of quenching.
- 2.45 What are the methods used for hardening low-carbon steels? Explain with reasons.
- 2.46 Explain the concepts of laser hardening. What are the applications of laser hardening?

3

Metal-Casting Processes

Objectives

Metal-casting processes are the primary manufacturing processes that are used to make complex parts utilizing liquid metal. After completing the chapter, the reader will be able to

- ▶ Understand the history of metal-casting processes
- ▶ Design patterns and cores for metal-casting processes
- ▶ Understand the various moulding materials used in the making of moulds and cores

3.1 INTRODUCTION

Casting is one of the earliest metal-shaping methods known to human beings. It generally means pouring molten metal into a refractory mould with a cavity of the shape to be made, and allowing it to solidify. When solidified, the desired metal object is taken out from the refractory mould either by breaking the mould or by taking the mould apart. The solidified object is called *casting*. This process is also called founding.

3.1.1 History of Casting Process

The casting process was probably discovered around c 3500 BC in Mesopotamia. In many parts of the world during that period, copper axes and other flat objects were turned out in open moulds made of stone or baked clay. These moulds were essentially in single piece. But in later periods, when round objects were required to be made, such moulds were split into two or more parts to facilitate the withdrawal of the round objects.

The Bronze age (c 2000 BC) brought far more refinement into the casting process. For the first time perhaps, a core for making hollow pockets in the objects was invented. These cores were made of baked clay. Also, the *cire perdue* or lost wax process was extensively used for making ornaments and fine work.

The casting technology has been greatly improved by the Chinese from around 1500 BC. Before that, there is no evidence of any casting activity found in China. They do not appear to have been greatly familiar with the *cire perdue* process nor used it extensively but instead specialized in multi-piece moulds for making highly intricate jobs. They spent a lot of time in perfecting the mould to the last detail so that hardly any finishing work was required on the casting made from the moulds. They probably made piece moulds

containing carefully fitted pieces, numbering thirty or more. In fact, many such moulds have been unearthed during archaeological excavations in various parts of China.

Indus Valley Civilization is also known for its extensive use of casting of copper and bronze for ornaments, weapons, tools and utensils. But there was not much of improvement in the technology. From the various objects and figurines that were excavated from the Indus Valley sites, they appear to have been familiar with all the known casting methods such as open mould, piece mould and the *cire perdue* process.

Though India could be credited with the invention of crucible steel, not much of iron founding was evident in India. There is evidence that iron founding had started around 1000 BC in Syria and Persia. It appears that iron-casting technology in India has been in use from the times of the invasion of Alexander the Great, around 300 BC.

The famous iron pillar presently located near the Qutb minar in Delhi is an example of the metallurgical skills of ancient Indians. It is 7.2 m long and is made of *pure malleable iron*. This is assumed to be of the period of Chandragupta II (375–413 AD) of the Gupta dynasty. The rate of rusting of this pillar, which stands outside in open air is practically zero and even the buried portion is rusting at an extremely slow rate. This must have been first cast and then hammered to the final shape.

3.1.2 Advantages and Limitations

The casting process is extensively used in manufacturing because of its many advantages. Molten material flows into any small section in the mould cavity and as such, any intricate shape—internal or external—can be made with the casting process. It is possible to cast practically any material, be it ferrous or non-ferrous. Further, the necessary tools required for casting moulds are very simple and inexpensive. As a result, for trial production or production of a small lot, it is an ideal method. It is possible in casting process, to place the amount of material where it is exactly required. As a result, weight reduction in design can be achieved. Castings are generally cooled uniformly from all sides and therefore they are expected to have no directional properties. There are certain metals and alloys, which can only be processed by casting and not by any other process like forging because of the metallurgical considerations. Castings of any size and weight, even up to 200 tons can be made.

However, the dimensional accuracy and surface finish achieved by normal sand-casting process would not be adequate for final application in many cases. To take these cases into consideration, some special casting processes such as diecasting have been developed, the details of which are given in later chapters. Also, the sand-casting process is labour intensive to some extent and therefore many improvements are aimed at it, such as machine moulding and foundry mechanization. With some materials it is often difficult to remove defects arising out of the moisture present in sand castings.

3.1.3 Applications

Typical applications of the sand-casting process are cylinder blocks, liners, machine tool beds, pistons, piston rings, mill rolls, wheels, housings, water supply pipes and specials, and bells.

3.1.4 Casting Terms

In the following chapters the details of sand-casting, which represents the basic process of casting would be seen. Before going into the details of the process, defining a number of casting vocabulary words would be appropriate. Refer to Fig. 3.1.

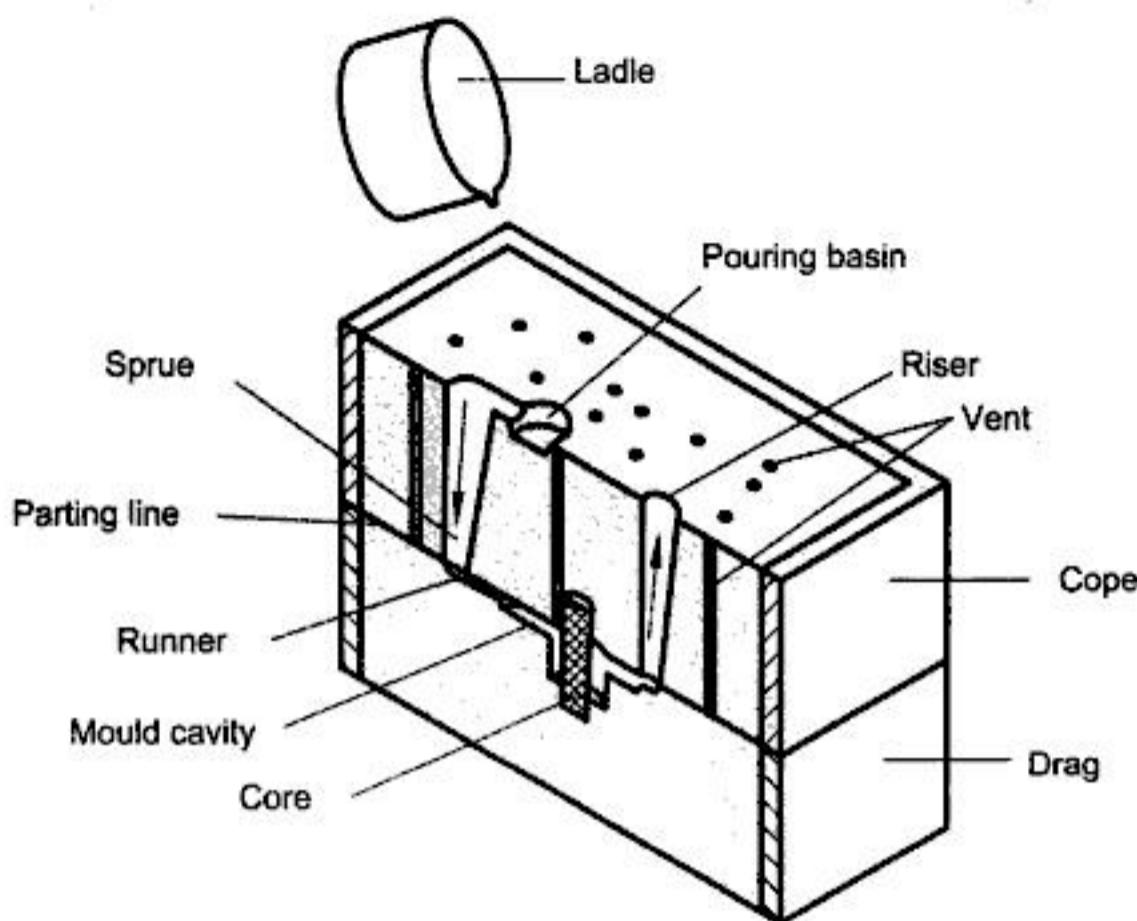


Fig. 3.1 Cross section of a sand mould ready for pouring

Flask A moulding flask is one which holds the sand mould intact. Depending upon the position of the flask in the mould structure, it is referred by various names such as drag, cope and cheek. It is made up of wood for temporary applications or more generally of metal for long-term use.

Drag Lower moulding flask.

Cope Upper moulding flask.

Cheek Intermediate moulding flask used in three-piece moulding.

Pattern Pattern is a replica of the final object to be made with some modifications. The mould cavity is made with the help of the pattern.

Parting line This is the dividing line between the two moulding flasks that makes up the sand mould. In split pattern it is also the dividing line between the two halves of the pattern.

Bottom board This is a board normally made of wood, which is used at the start of the mould making. The pattern is first kept on the bottom board, sand is sprinkled on it and then the ramming is done in the drag.

Facing sand The small amount of carbonaceous material sprinkled on the inner surface of the moulding cavity to give better surface finish to the castings.

Moulding sand It is the freshly prepared refractory material used for making the mould cavity. It is a mixture of silica, clay and moisture in appropriate proportions to get the desired results and it surrounds the pattern while making the mould.

Backing sand It is what constitutes most of the refractory material found in the mould. This is made up of used and burnt sand.

Core It is used for making hollow cavities in castings.

Pouring basin A small funnel-shaped cavity at the top of the mould into which the molten metal is poured.

Sprue The passage through which the molten metal from the pouring basin reaches the mould cavity. In many cases it controls the flow of metal into the mould.

Runner The passageways in the parting plane through which molten metal flow is regulated before they reach the mould cavity.

Gate The actual entry point through which molten metal enters the mould cavity.

Chaplet Chaplets are used to support cores inside the mould cavity to take care of its own weight and overcome the metallostatic forces.

Chill Chills are metallic objects, which are placed in the mould to increase the cooling rate of castings to provide uniform or desired cooling rate.

Riser It is a reservoir of molten metal provided in the casting so that hot metal can flow back into the mould cavity when there is a reduction in volume of metal due to solidification.

3.1.5 Sand Mould Making Procedure

The procedure for making a typical sand mould is described in the following steps.

First, a bottom board is placed either on the moulding platform or on the floor, making the surface even. The drag moulding flask is kept upside down on the bottom board along with the drag part of the pattern at the centre of the flask on the board. There should be enough clearance between the pattern and the walls of the flask which should be of the order of 50 to 100 mm. Dry facing sand is sprinkled over the board and pattern to provide a nonsticky layer. Freshly prepared moulding sand of requisite quality is now poured into the drag and on the pattern to a thickness of 30 to 50 mm. The rest of the drag flask is completely filled with the backup sand and uniformly rammed to compact the sand. The ramming of the sand should be done properly so as not to compact it too hard, which makes the escape of gases difficult, nor too loose, so that the mould would not have enough strength. After the ramming is over, the excess sand in the flask is completely scraped using a flat bar to the level of the flask edges.

Now, with a vent wire, which is a wire of 1- to 2-mm diameter with a pointed end, vent holes are made in the drag to the full depth of the flask as well as to the pattern to facilitate the removal of gases during casting solidification. This completes the preparation of the drag.

The finished drag flask is now rolled over to the bottom board exposing the pattern as shown in Fig. 3.2(c). Using a slick, the edges of sand around the pattern is repaired and the cope half of the pattern is placed over the drag pattern, aligning it with the help of dowel pins. The cope flask on top of the drag is located aligning again with the help of the pins. The dry parting sand is sprinkled all over the drag and on the pattern.

A sprue pin for making the sprue passage is located at a small distance of about 50 mm from the pattern. Also, a riser pin if required is kept at an appropriate place and freshly prepared moulding sand similar to that of the drag along with the backing sand is sprinkled. The sand is thoroughly rammed, excess sand scraped and vent holes are made all over in the cope as in the drag.

The sprue pin and the riser pin are carefully withdrawn from the flask. Later, the pouring basin is cut near the top of the sprue. The cope is separated from the drag and any loose sand on the cope and drag interface of the drag is blown off with the help of bellows. Now, the cope and the drag pattern halves are withdrawn by using the draw spikes and rapping the pattern all around to slightly enlarge the mould cavity so that the mould walls are not spoiled by the withdrawing pattern. The runners and the gates are cut in the mould carefully without spoiling the mould. Any excess or loose sand found in the runners and mould cavity is blown away using the bellows. Now, the facing sand in the form of a paste is applied all over the mould cavity and the runners, which would give the finished casting a good surface finish.

A dry sand core is prepared using a core box. After suitable baking, it is placed in the mould cavity as shown in Fig. 3.2. The cope is replaced on the drag taking care of the alignment of the two by means of the pins. A suitable weight is kept on the cope to take care of the upward metallostatic force during the pouring of molten metal. The mould now, as shown in Fig. 3.2(e) is ready for pouring.

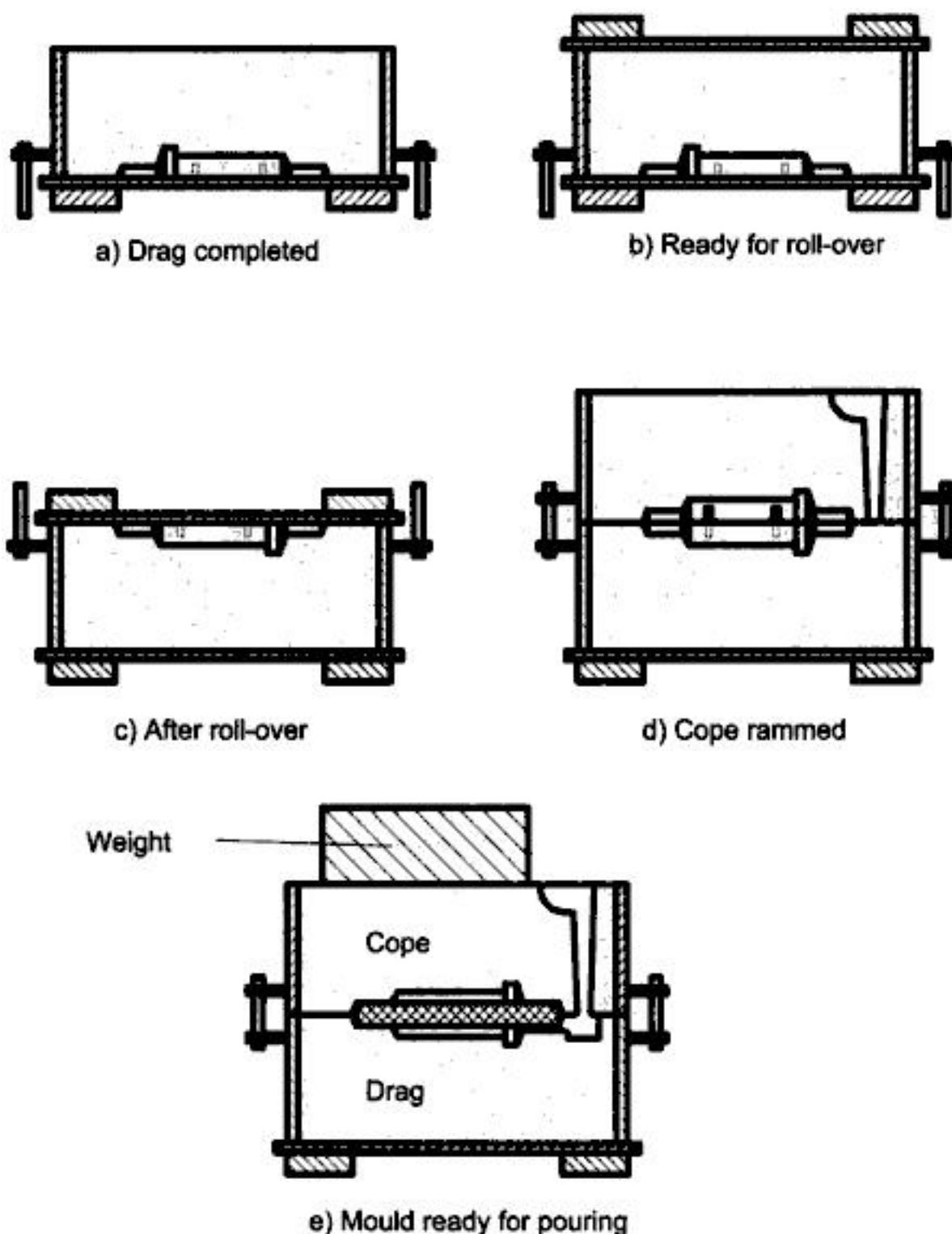


Fig. 3.2 Sand-mould-making procedure

3.2

PATTERNS

As has been defined earlier, a pattern is a replica of the object to be made by the casting process, with some modifications. The main modifications are

- the addition of pattern allowances,
- the provision of core prints, and

- c) elimination of fine details, which cannot be obtained by casting and hence are to be obtained by further processing.

3.2.1 Pattern Allowances

The dimensions of the pattern are different from the final dimensions of the casting required. This is required because of the various reasons. These are detailed as follows.

Shrinkage All metals shrink when cooling except perhaps bismuth. This is because of the inter-atomic vibrations which are amplified by an increase in temperature. However, there is a distinction to be made between liquid shrinkage and solid shrinkage.

Liquid shrinkage refers to the reduction in volume when the metal changes from liquid to solid state at the solidus temperature. To account for this, risers are provided in the moulds as explained in Chapter 4.

Solid shrinkage is the reduction in volume caused, when a metal loses temperature in the solid state. The shrinkage allowance is provided to take care of this reduction.

The rate of contraction with temperature is dependent on the material. For example steel contracts to a higher degree compared to aluminium. The shrinkage is also dependent upon the metallurgical transformation taking place during the solidification. For example, white cast iron shrinks by about 21.0 mm/m during casting. However, when annealed it grows by about 10.5 mm/m, resulting in a net shrinkage of 10.5 mm/m. Similarly, in grey cast iron and spheroidal graphite iron, the amount of graphitization controls the actual shrinkage. When graphitization is more, the shrinkage would be less and vice versa. The various rates of contraction for the materials are given in Table 3.1.

Table 3.1 Shrinkage allowances for various metals

Material	Pattern dimension, mm	Section thickness, mm	Shrinkage allowance, mm/m
Grey cast iron	up to 600	—	10.5
	600 to 1200	—	8.5
	over 1200	—	7.0
White cast iron	—	—	16.0 to 23.0
Ductile iron	—	—	8.3 to 10.4
Malleable iron	—	6	11.8
		9	10.5
		12	9.2
		15	7.9
		18	6.6
		22	4.0
		25	2.6
		—	—
Plain carbon steel	up to 600	—	21.0
	600 to 1800	—	16.0

(Continued)

Table 3.1 (Continued)

Material	Pattern dimension, mm	Section thickness, mm	Shrinkage allowance, mm/m
	over 1800	—	13.0
Chromium steel	—	—	20.0
Manganese steel	—	—	25.0 to 38.0
Aluminium	—	—	13.0
Aluminium bronze	—	—	20.0 to 23.0
Copper	—	—	16.0
Brass	—	—	15.5
Bronze	—	—	15.5 to 22.0
Gunmetal	—	—	10.0 to 16.0
Manganese bronze	—	—	15.6
Silicon bronze	—	—	10.4
Tin bronze	—	—	10.4
Chromium copper	—	—	20.8
Lead	—	—	26.0
Monel	—	—	20.0
Magnesium	—	—	13.0
Magnesium alloys	—	—	16.0
White metal	—	—	6.0
Zinc	—	—	10.0 to 15.0

As a rule, all the dimensions are going to be altered uniformly unless they are restrained in some way. For example, a dry sand core at the centre of the casting may restrain the casting from contracting but the edges are not restrained. Thus, it may be desirable to provide a higher shrinkage allowance for outer dimensions compared to those, which may be restrained. The actual value of shrinkage depends on various factors specific to a particular casting, namely, the actual composition of the alloy cast, mould materials used, mould design, complexity of the pattern and the component size. The pattern-maker's experience and a little bit of trial are to be used in arriving at the final shrinkages provided on the pattern. The values shown in Table 3.1 are average values and higher values are to be used for smaller dimensions and vice versa.

The shrinkage allowance is always to be added to the linear dimensions. Even in case of internal dimensions (e.g., internal diameters of cylinders), the material has a tendency to contract towards the centre and thus are to be increased. It is also possible to obtain shrink rulers for specific materials such as steels, which are nothing but special scales where dimensions shown are actually longer by a measure equal to the shrinkage allowance. Dimensions provided by such a rule can be used at the time of making the pattern. Different shrink rulers are used for different casting materials.

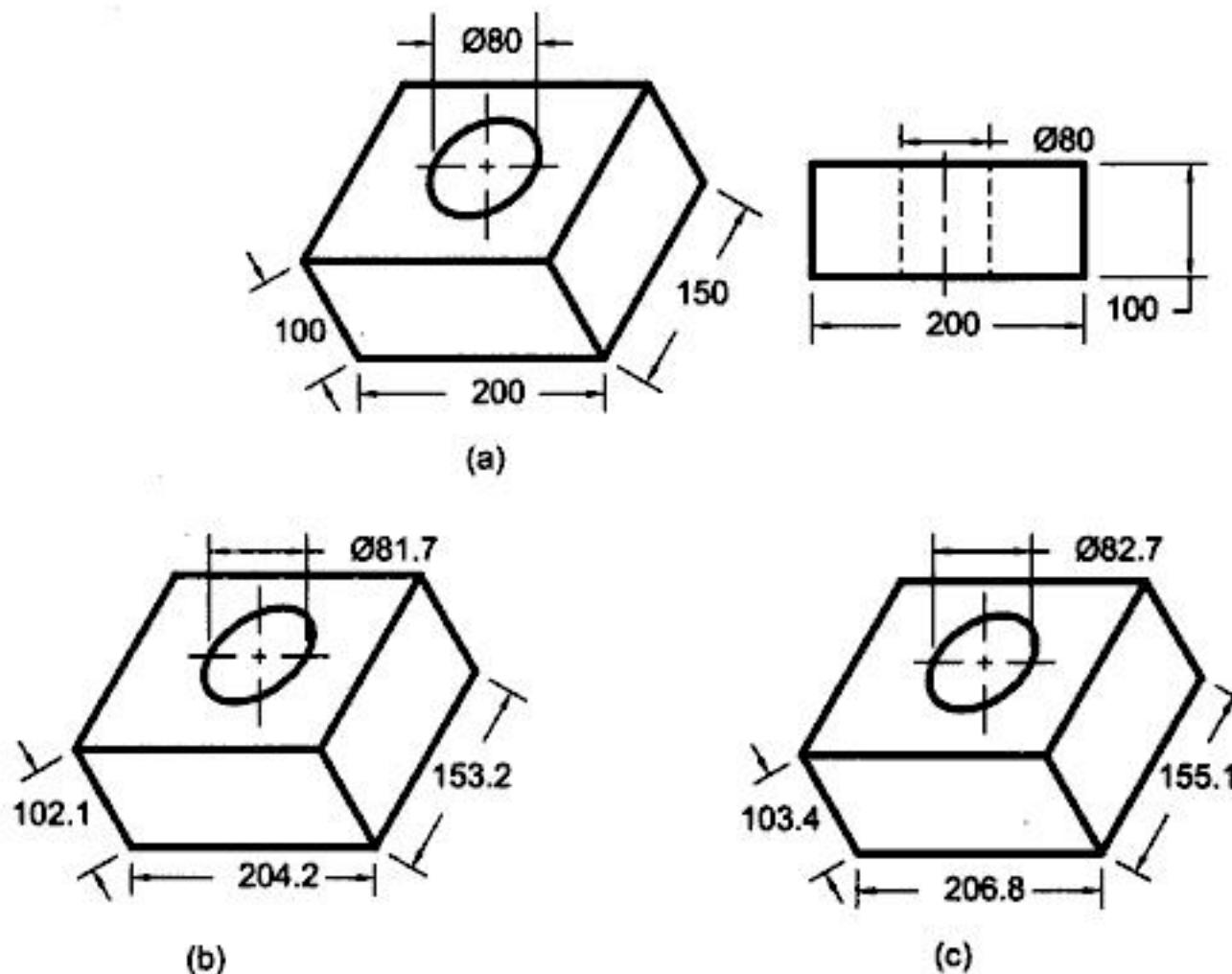


Fig. 3.3 Provision of allowances for patterns in sand castings (All dimensions in mm)

|| Example 3.1 || The casting shown in Fig. 3.3(a) is to be made in plain carbon steel using a wooden pattern. Assuming only shrinkage allowance, calculate the dimensions of the pattern.

Solution From Table 3.1, for steel the shrinkage allowance is 21.0 mm/m.

For dimension 200, allowance is $200 \times 21.0 / 1000 = 4.20$ mm

For dimension 150, allowance is $150 \times 21.0 / 1000 = 3.15 \approx 3.20$ mm

For dimension 100, allowance is $100 \times 21.0 / 1000 = 2.10$ mm

For dimension 80, allowance is $80 \times 21.0 / 1000 = 1.68 \approx 1.70$ mm

The pattern drawing with required dimensions taking shrinkage into account is shown in Fig. 3.3(b).

Double shrinkage allowance is to be provided on the pattern dimensions, if it is to be used for casting the metallic pattern, which would ultimately be used for moulding to take care of the shrinkage of the actual metal cast as well as the shrinkage of the pattern metal. This is illustrated in the following example.

|| Example 3.2 || For the same example as shown in Fig. 3.3(a), if the master pattern is to be made of aluminium, calculate the dimensions of the wooden pattern which is to be used for making the aluminium pattern.

Solution Fig. 3.3(b) shows the dimensions of the aluminium pattern.

From Table 3.1, for aluminium the shrinkage allowance is 13.0 mm/m. For plain carbon steel, it is 21.0 mm/m. The total shrinkage = $13.0 + 21.0 = 34.0$ mm/m

For dimension 200, allowance is $200 \times 34.0 / 1000 = 6.80$ mm

For dimension 150, allowance is $150 \times 34.0 / 1000 = 5.10$ mm

For dimension 100, allowance is $100 \times 34.0 / 1000 = 3.40$ mm

For dimension 80, allowance is $80 \times 34.0 / 1000 = 2.72$ mm

The final dimensions of the wooden pattern for making the aluminium master pattern are shown in Fig. 3.3(c). The pattern allowance applied for this wooden pattern is called double shrinkage allowance.

Finish or Machining Allowance The finish and accuracy achieved in sand casting are generally poor and therefore when the casting is functionally required to be of good surface finish or dimensionally accurate, it is generally achieved by subsequent machining. Also, ferrous materials would have scales on the skin, which are to be removed by cleaning. Hence, extra material is to be provided which is to be subsequently removed by machining or cleaning process. This depends on dimensions, the type of casting material and the finish required. This may range from 2 to 20 mm. General guidelines for machining allowances are provided in the Table 3.2. The machining allowance provided would ultimately have to be removed by machining. Hence, the cost of providing additional machining allowance should be carefully examined before finalizing.

Table 3.2 *Machining allowances on patterns for sand castings*

Dimension, mm	Allowance, mm		
	Bore	Surface	Cope side
Cast iron			
upto 300	3.0	3.0	5.5
301 to 500	5.0	4.0	6.0
501 to 900	6.0	5.0	6.0
Cast steel			
upto 150	3.0	3.0	6.0
151 to 500	6.0	5.5	7.0
501 to 900	7.0	6.0	9.0
Non ferrous			
upto 200	2.0	1.5	2.0
201 to 300	2.5	1.5	3.0
301 to 900	3.0	2.5	3.0

The type of machining allowance provided would depend on the metal cast, the type of moulding used, the class of accuracy required on the surface and the complexity of surface details. One way of reducing the machining allowance is to keep entire the casting in the drag flask such that dimensional variation and other defects due to the parting plane are reduced to a minimum.

|| Example 3.3 || In the previous example, what will be the pattern dimension if all the surfaces of the casting need to be machined?

Solution From Table 3.2,

Machining allowance for bore = 3 mm

Machining allowance for all surfaces = 3 mm

Machining allowance for cope side = 6 mm

The dimension 80, $80 + 2 \times 3 = 86$ mm

The dimension 100, $100 + 3 + 6 = 109$ mm

The dimension 150, $150 + 3 + 3 = 156$ mm



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shows an example of the provision of core prints. The size of the core prints to be provided is to be estimated based on the specific casting, the details of which are provided later.

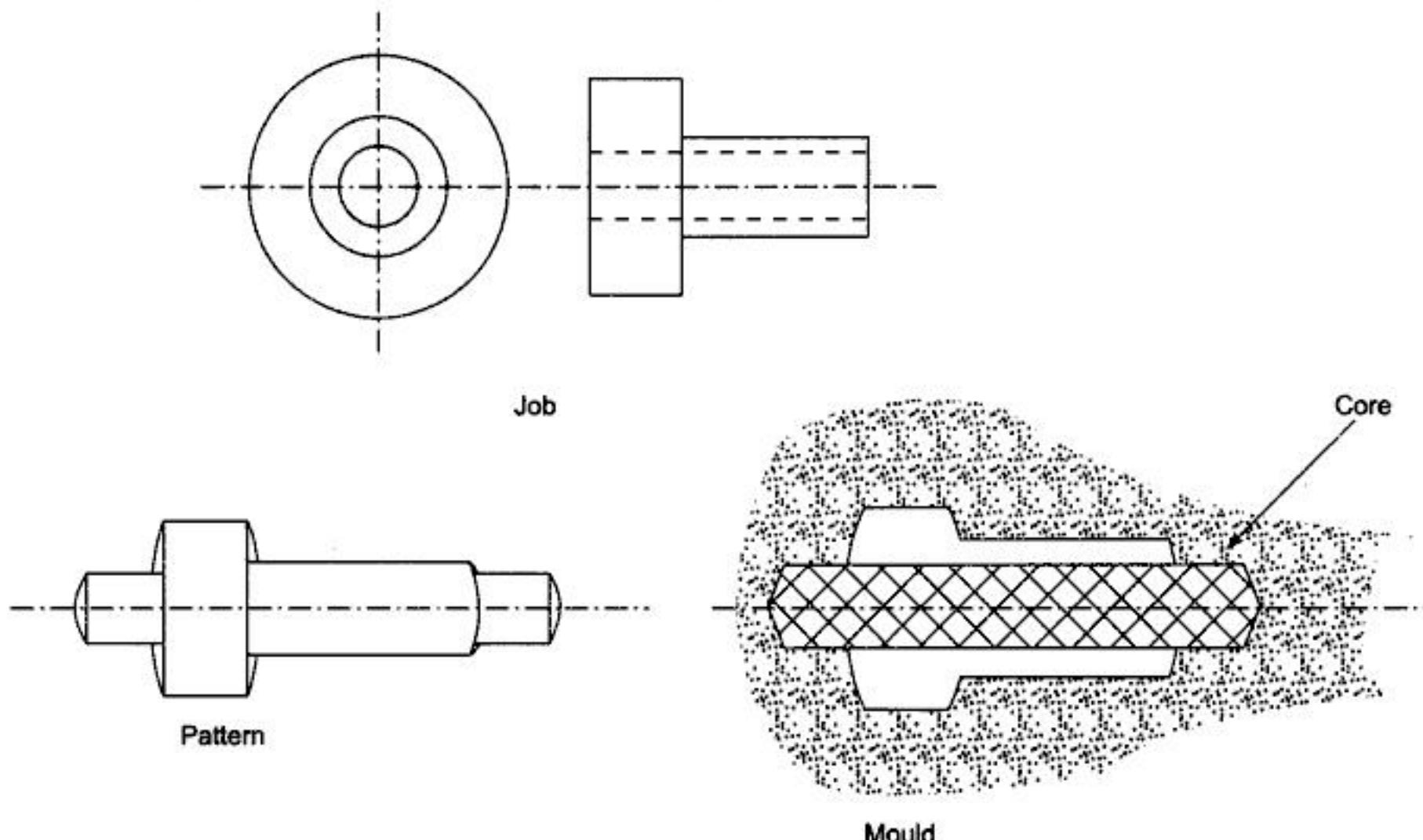


Fig. 3.7 Typical job, its pattern and the mould cavity

3.2.3 Elimination of Details

Often it is not possible to get very fine details on the surface or very small holes by sand casting. In such cases, it is desirable to simplify the casting process by eliminating those details and get them during the finishing process employed. One such example is presented in Fig. 3.8. The types of details that one would like to eliminate in the casting depend on the required accuracy, the capability of the chosen casting process and the moulding method employed.

3.2.4 Pattern Materials

The usual pattern materials are wood, metal and plastics. The most commonly used pattern material is wood, the main reason being the easy availability and the low weight. Also, it can be easily shaped and is relatively cheap. But the main disadvantage of wood is its absorption of moisture as a result of which distortions and dimensional changes occur. A good construction may be able to reduce the warpage to some extent. Hence, proper seasoning and upkeep of wood is almost a pre-requisite for large-scale use of wood as a pattern material.

The usual varieties of wood commonly used for making patterns are pine, mahogany, teak, walnut and deodar. Besides the wood, the plywood boards of the veneer type as well as the particle boards are also used for making patterns. Because of their availability in various thicknesses, their higher strength and no need for seasoning are the reasons for their usage. However, they can be used only in patterns which are of flat type (pattern plates) and no three-dimensional contours.

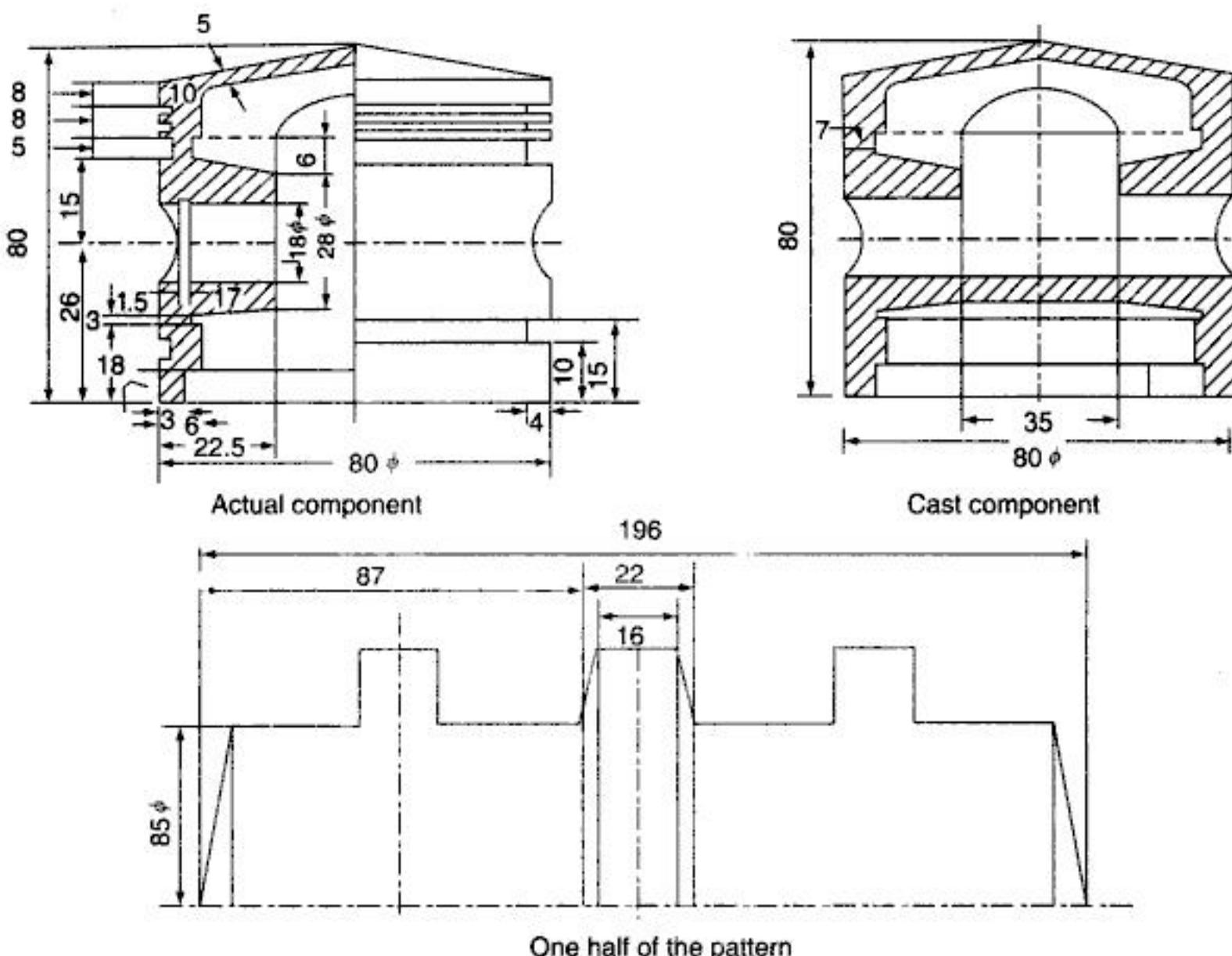


Fig. 3.8 Elimination of details on a casting to simplify moulding

The choice of the pattern material depends essentially on the size of the casting, the number of castings to be made from the pattern, and the dimensional accuracy required. For very large castings, wood may be the only practical pattern material. Moulding sand being highly abrasive for large-scale production, wood may not be suitable as a pattern material and one may have to opt for metal patterns.

Because of their durability and smooth surface finish, metal patterns are extensively used for large-scale casting production and for closer dimensional tolerances. Though many materials such as cast iron, brass, etc., can be used as pattern materials, aluminium and white metal are most commonly used. These are light, can be easily worked, and are corrosion resistant. Since white metal has very small shrinkage, the white metal pattern can be made use of for making additional patterns without worrying about the double shrinkage allowances. Most metal patterns are cast in sand moulds from a master wood pattern provided with the double shrinkage allowance. A comparative study of the advantages and disadvantages of various pattern materials is shown in Table 3.4.

Plastics are also used as pattern materials because of their low weight, easier formability, smooth surfaces and durability. They do not absorb moisture and are therefore, dimensionally stable and can be cleaned easily. The making of a plastic pattern can be done in sand clay moulds or moulds made of Plaster of Paris. The most generally used plastics are cold setting epoxy resins with suitable fillers. With a proper combination it is possible to obtain a no shrink plastic material. In such a case, double shrinkage allowances may not be required.

Table 3.4 Comparative characteristics of metallic pattern materials

Pattern metal	Advantages	Disadvantages
Aluminium alloys	Good machinability	Low strength
	High corrosion resistance	High cost
	Low density Good surface finish	
Grey cast iron	Good machinability	Corrosion prone
	High strength	High density
	Low cost	
Steel	Good surface finish	Corrosion prone
	High strength	High density
Brass and bronze	Good surface finish	High cost
	High strength	High density
	High corrosion resistance	
Lead alloys	Good machinability	High cost
		High density
		Low strength

Polyurethane foam is also used as pattern material. It is very light and can be easily formed into any shape required. It can be used for light duty work for small number of castings for the conventional casting and for single casting in the case of full mould process where the pattern is burned inside the mould without withdrawing. This plastic has a very low ash content and hence can be burned inside the mould.

The pattern material is to be chosen based on the expected life of the pattern. The following Table 3.5 gives comparative values of pattern material choices.

Table 3.5 Pattern materials based on expected life

Number of castings produced before pattern equipment repair		
Pattern	Core	Pattern Material
Small castings (under 600 mm)		
2 000	2 000	Hard wood
6 000	6 000	Aluminium, Plastic
100 000	100 000	Cast iron
Medium castings (600–1800 mm)		
1 000	750	Hard wood
3 000	3 000	Aluminium, Plastic
Large castings (above 1800 mm)		
200	150	Soft wood
500	500	Hard wood metal reinforced



3.2.5 Types of Patterns

There are various types of patterns depending upon the complexity of the job, the number of castings required and the moulding procedure adopted.

Single piece pattern These are inexpensive and the simplest type of patterns. As the name indicates, they are made of a single piece as shown in Fig. 3.9. This type of pattern is used only in cases where the job is very simple and does not create any withdrawal problems. It is also used for applications in very small-scale production or in prototype development. This pattern is expected to be entirely in the drag. One of the surfaces is expected to be flat which is used as the parting plane. If no such flat surface exists, the moulding may become complicated with the necessity of a follow board as explained later.

Split Pattern or Two Piece Pattern This is the most widely used type of pattern for intricate castings. When the contour of the casting makes its withdrawal from the mould difficult, or when the depth of the

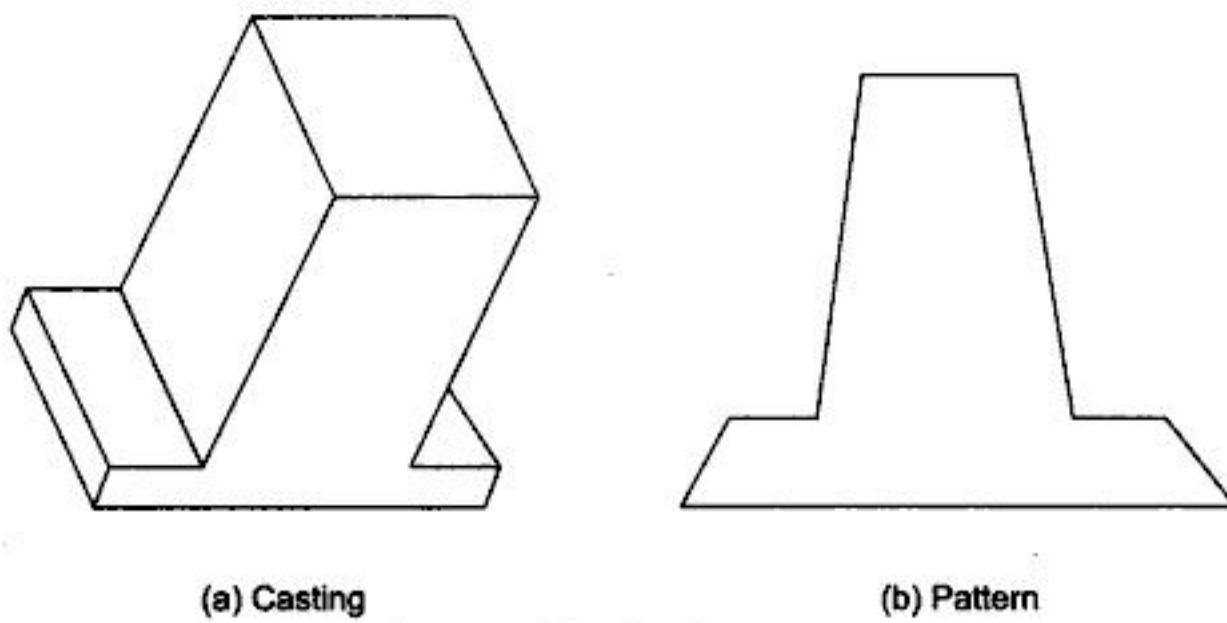


Fig. 3.9 Single-piece pattern

casting is too high, then the pattern is split into two parts so that one part is in the drag and the other in the cope. The split surface of the pattern is the same as the parting plane of the mould. The two halves of the pattern should be aligned properly by making use of the dowel pins, which are fitted to the cope half. These dowel pins match with the precisely made holes in the drag half of the pattern and thus align the two halves properly as seen in Fig. 3.10.

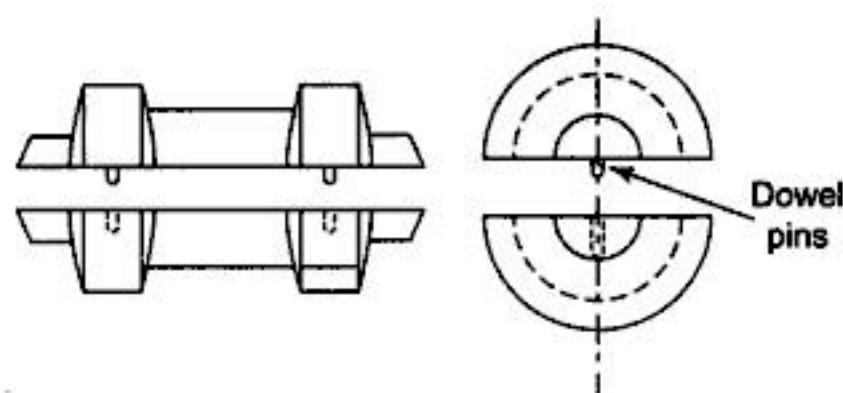


Fig. 3.10 Split pattern

Gated Pattern This is an improvement over the simple pattern where the gating and runner system are integral with the pattern. This would eliminate the hand cutting of the runners and gates and help in improving the productivity of a moulder.

Cope and Drag Pattern These are similar to split patterns. In addition to splitting the pattern, the cope and drag halves of the pattern along with the gating and risering systems are attached separately to the metal or wooden plates along with the alignment pins (Fig. 3.11). They are called the *cope* and *drag patterns*. The cope and drag moulds may be produced using these patterns separately by two moulders but they can be assembled to form a complete mould. These types of patterns are used for castings, which are heavy and inconvenient for handling as also for continuous production.

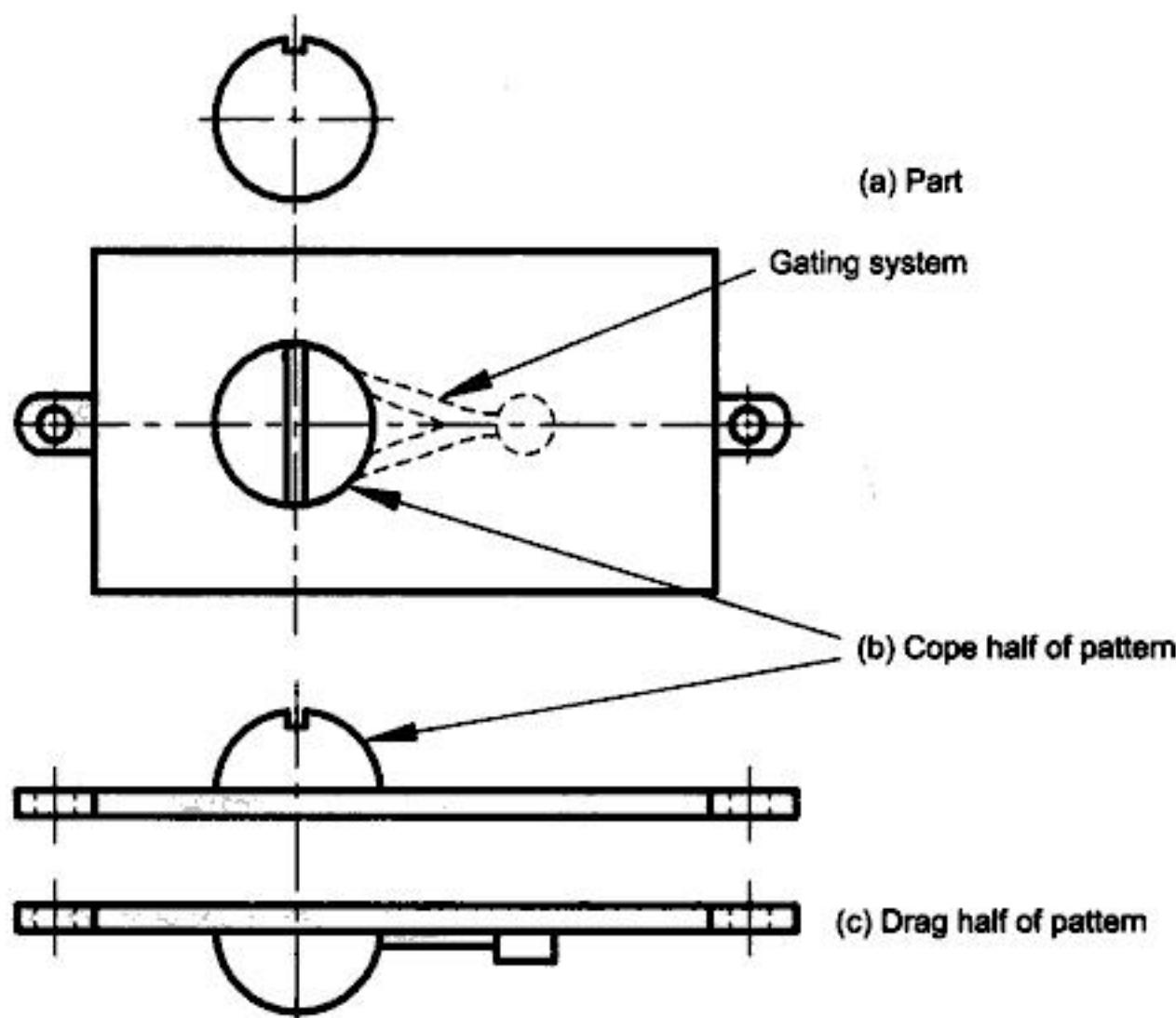


Fig. 3.11 Cope and drag pattern

Match Plate Pattern These are extensions of the previous type. Here, the cope and drag patterns along with the gating and the risering are mounted on a single matching metal or wooden plate on either side as shown in Fig. 3.12. On one side of the match plate the cope flask is prepared and on the other, the drag flask. After moulding when the match plate is removed, a complete mould with gating is obtained by joining the cope and the drag together.

The complete pattern with match plate is entirely made of metal, usually aluminium for its light weight and machinability. But when dimensions are critical, the match plate may be made of steel with necessary case hardening of the critical wear points. The pattern and gating are either screwed to the match plate in the



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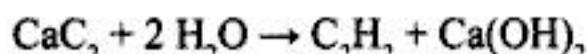
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The acetylene (C_2H_2) coming out will be collected in the space above the sand raising the pressure. A pressure gauge connected to the apparatus would give directly the amount of acetylene generated, which is proportional to the moisture present. It is possible to calibrate the pressure gauge (or manometer) to directly read the amount of moisture.

Clay Content The clay content of moulding sand is determined by dissolving or washing it off the sand. To determine the clay percentage, a 50-g sample is dried at 105 to 110°C and the dried sample is taken in a 1 litre glass flask and added with 475 ml of distilled water and 25 ml of a 1% solution of caustic soda (NaOH 25 g per litre). This sample is thoroughly stirred.

After stirring for a period of 5 minutes, the sample is diluted with fresh water up to a 150-mm graduation mark and the sample is left undisturbed for 10 minutes to settle. The sand settles at the bottom and the clay particles washed from the sand would be floating in the water. 125 mm of this water is siphoned off the flask and it is again topped to the same level and allowed to settle for 5 minutes. The above operation is repeated till the water above the sand becomes clear, which is an indication that all the clay in the moulding sand has been removed. Now, the sand is removed from the flask and dried by heating. The difference in weight of the dried sand and 50 g when multiplied by two gives the clay percentage in the moulding sand.

Sand-Grain Size To find out the sand-grain size, a sand sample which is devoid of moisture and clay such as the one obtained after the previous testing is to be used. The dried clay free sand grains are placed on the top sieve of a sieve shaker, which contains a series of sieves one upon the other with gradually decreasing mesh sizes. The mesh sizes are standardized as shown in Table 3.10. The sieves are shaken continuously for a period of 15 minutes. After this shaking operation, the sieves are taken apart and the sand left over on each of the sieve is carefully weighed.

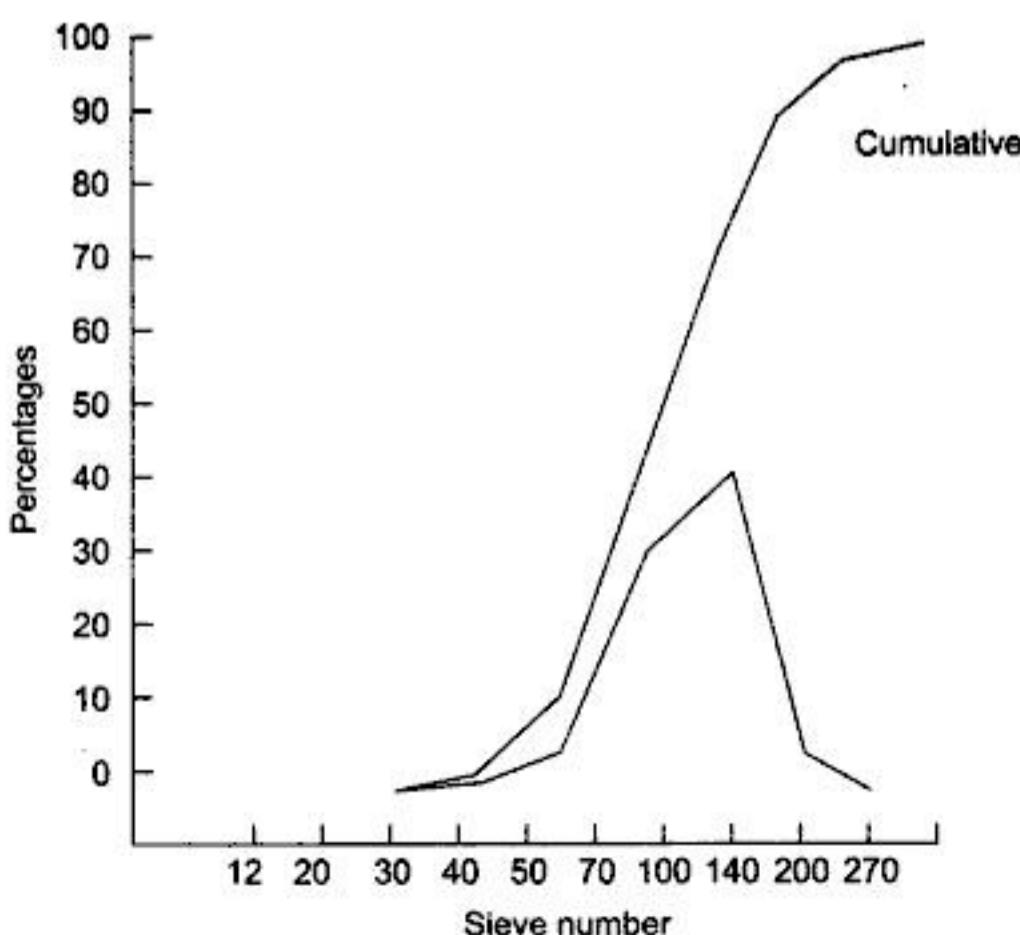


Fig. 3.19 Sand-grain size distribution



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Besides these, there are other tests to determine such properties as deformation, green tensile strength, hot strength, expansion, etc. The details of these testing methods can be found in the references cited at the end of this chapter.

3.3.3 Sand Preparation

One of the important requirements for the preparation of sand is a thorough mixing of its various ingredients. This is essential to ensure uniform distribution of the various components in the entire bulk of the sand.

During the mixing process, any lump present in sand is broken up and clay is uniformly enveloped around the sand grains and moisture is uniformly distributed. Besides manual mixing, an equipment called mueller is normally used in foundries to mix the sands. These are essentially of two types, batch type and continuous.

As shown in Fig. 3.21, a batch Mueller consists of one or two Mueller wheels and an equal number of plough blades, all of them connected to a single driving source. The Mueller wheels are large and heavy, and continuously roll inside the Mueller bowl. The plough blades ensure that the sand is continuously agitated. The combined action of both these is a sort of kneading action, which makes the clay and the moisture uniformly distributed throughout the sand.

A continuous Mueller consists of two bowls with Mueller wheels and ploughs, such that sand, clay and moisture are fed through a hopper into one of the bowls which after getting mulled moves into the second one and then finally out. Thus, well-prepared moulding sand is continuously available for use. It is generally used for large-scale production.

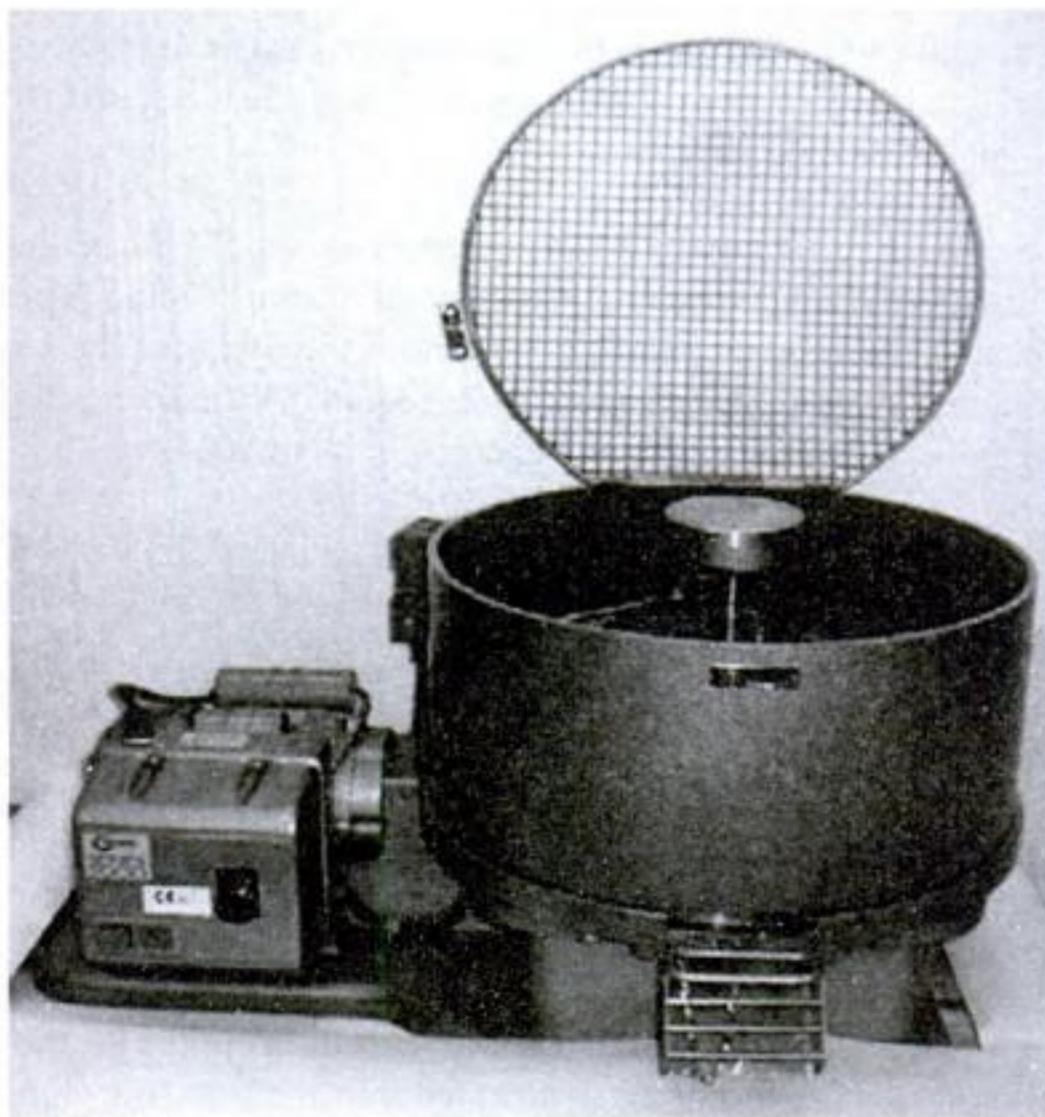


Fig. 3.21 Batch Mueller



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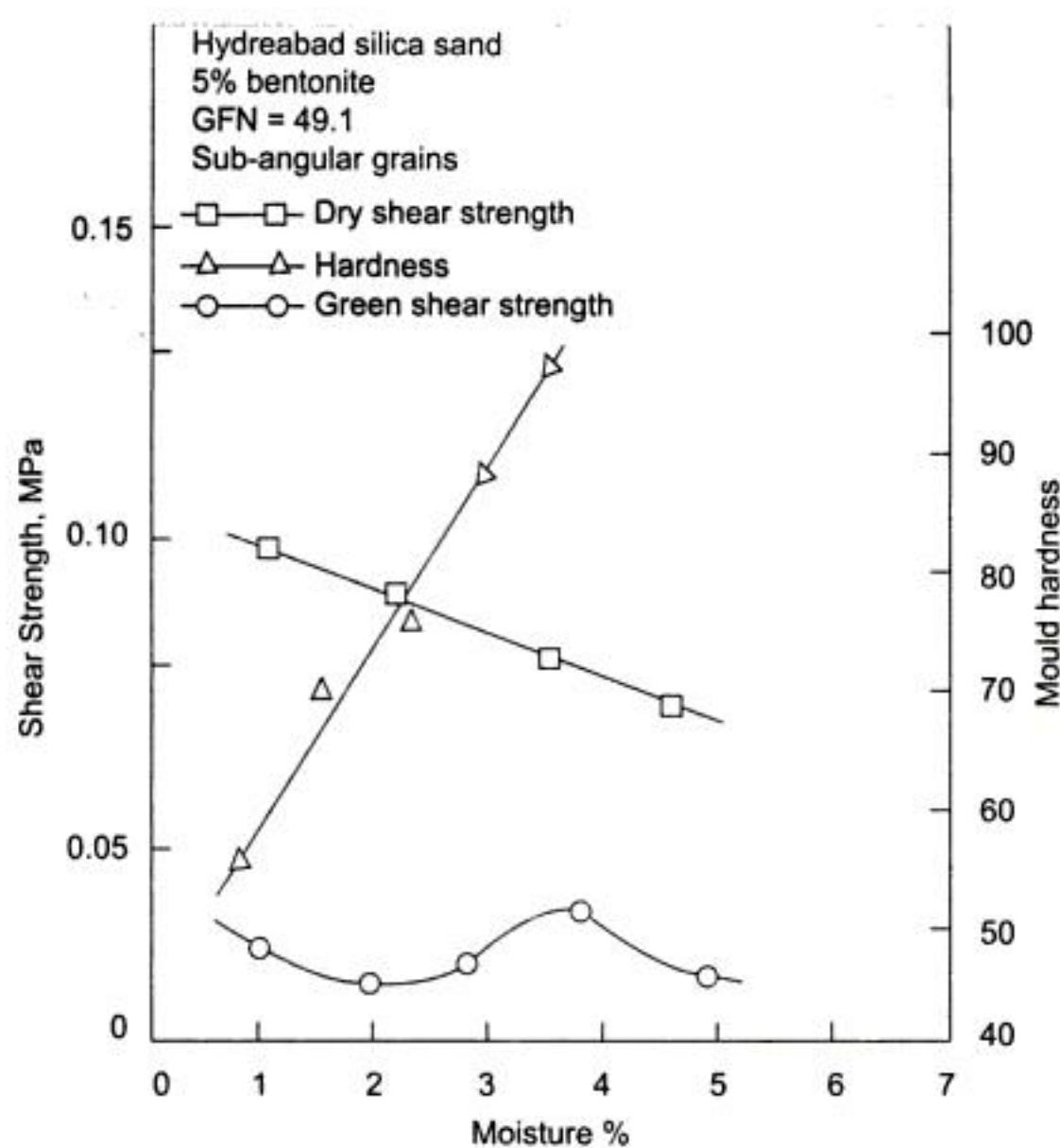


Fig. 3.30 Properties of Hyderabad sand

Table 3.16 High silica Indian sands (synthetic)

Sand location	Moisture %	Green permeability number	Green compression strength, kPa	Clay %	Fineness number GFN	Sintering Temperature °C	Grain type*	Usage
Rajkot	1.5–3.4	160–190	40–60	3	53	1350	—	Cast iron, steels
Hardwar	3–6	85	30–50	1	57	1250–1300	B,C	Steels
Brahmani river (Orissa)	2.5–4.5	150–500	20–50	0.4–3	28–78	1250–1350	B,C	Cast iron
Gidni (W.B.)	2.4–3.4	175–335	80–120	5.7	27	1150–1200	A,B	Steel with addition
Adjoy river (W.B.)	2.2–4	155	30–40	1.4	48.6	1200–1250	B,C	Cast iron
Yadgiri (A.P.)	1.3–3.3	130–180	40–70	3.2	78	1100–1150	B	Non-ferrous
Rajmahal (Bihar)	3.4	200	60	1.02	52	—	B	Steels

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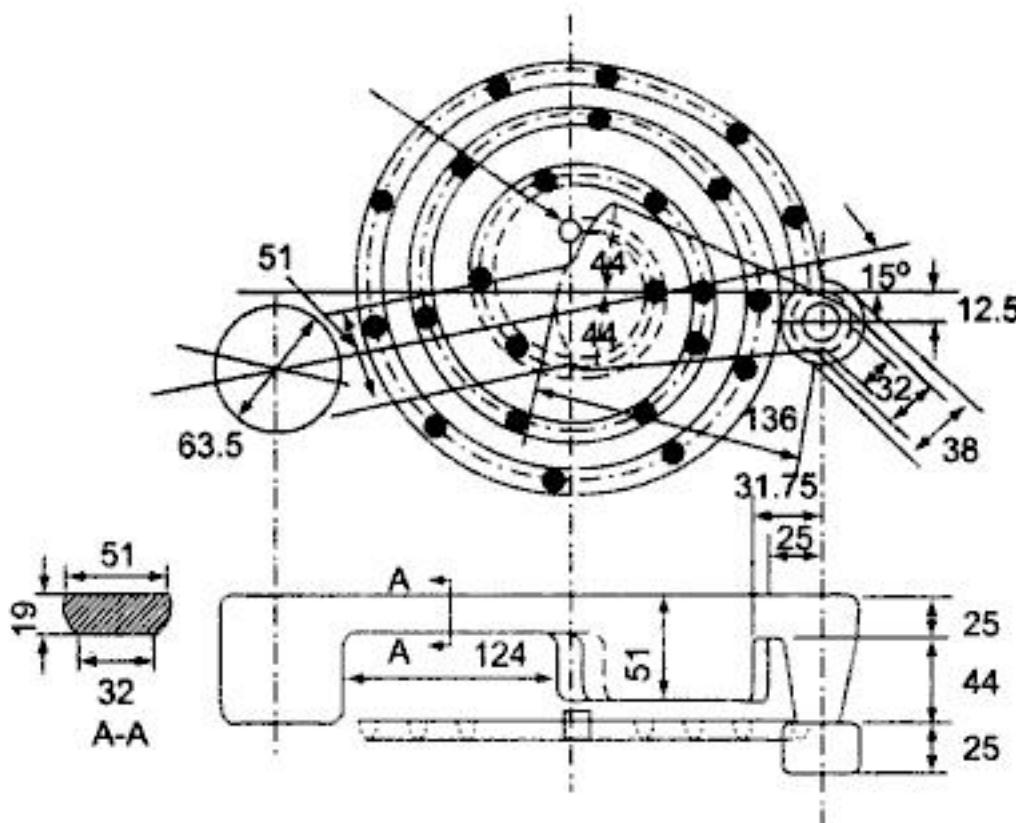


Fig. 3.33 Fluidity spiral design

Then the fluidity spiral length in cm can be estimated by means of the following empirical relation:

$$\text{Fluidity, cm} = 37.846 \times CF + 0.228 \times T - 389.6$$

where T = pouring temperature, °C

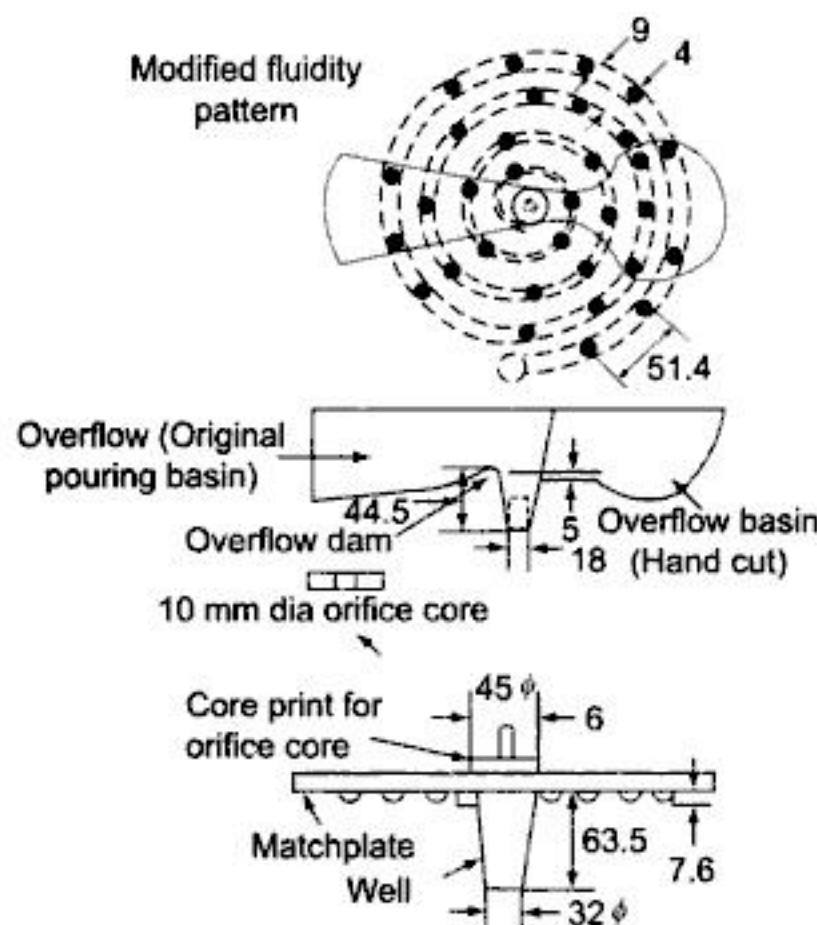


Fig. 3.34 Fluidity spiral for grey cast iron

The results obtained by Porter and Rosenthal for the fluidity of grey cast iron as affected by the composition and the melting temperatures are presented in Fig. 3.35.



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A combination of jolt-squeeze machines are more common in view of the more uniform ramming that could be achieved by combining the two methods as described above.

Sand slinging is done by throwing sand into the flask rapidly and with great force. This process develops uniformly high mould hardness. The process is very fast and gives high uniform sand ramming. The sand should be uniformly sprayed into the mould by moving the nozzle through the entire area of the flask. Also, it is necessary that the sand be sprayed in layers to achieve uniform hardness. However, the initial cost of the equipment is high compared to the other form of moulding machines described above.

3.4 CORES

Cores are the materials used for making cavities and hollow projections, which cannot normally be produced by the pattern alone. Any complicated contour or cavity can be made by means of cores so that really intricate shapes can be easily obtained. These are generally made of sand and are even used in permanent moulds. In general, cores are surrounded on all sides by the molten metal and are therefore subjected to much more severe thermal and mechanical conditions and as a result, the core sand should be of higher strength than the moulding sand.

The normal characteristics desired of a core are the following:

1. **Green Strength** A core made of green sand should be strong enough to retain the shape till it goes for baking.
2. **Dry Strength** It should have adequate dry strength so that when the core is placed in the mould, it should be able to resist the metal pressure acting on it.
3. **Refractoriness** Since in most cases, the core is surrounded all around it is desirable that the core material should have higher refractoriness.
4. **Permeability** Some of the gases evolving from the molten metal and generated from the mould may have to go through the core to escape out of the mould. Hence cores are required to have higher permeability.
5. **Collapsibility** As the casting cools, it shrinks, and unless the core has good collapsibility (ability to decrease in size) it is likely to provide resistance against shrinkage and thus can cause hot tears.
6. **Friability** After the casting is completely cooled, the core should be removed from the casting before it is processed further. Hence the friability (the ability to crumble) should also be a very important consideration.
7. **Smoothness** The surface of the core should be smooth so as to provide a good finish to the casting.
8. **Low Gas Emission** Because of the high temperatures to which a core is subjected to, it should allow only a minimal amount of gas to be evolved such that voids in the castings can be eliminated.

3.4.1 Core Sands

The core sand should contain sand grains, binders and other additives to provide specific properties.

Sand The silica sand which is completely devoid of clay is generally used for making core sands. Coarse silica, because of its higher refractoriness is used in steel foundries whereas the finer sands are used for cast irons and nonferrous alloys.

Binders As explained earlier, core sands need to be stronger than the moulding sand and therefore the clay binder used in moulding sands is not enough but somewhat better binders need to be used. The normal binders are organic in nature, because these would be burnt away by the heat of the molten metal and thus make the core



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In designing the core boxes, care should be taken to consider the strength of the core. Before the baking process, the core is generally weak and should be well supported. If the core is simple and strong in itself, no special precaution is required. But for slender and complicated cores, it may be necessary to place the core in the core box during the baking process. In such a situation the core box should be small. An example of a core box is shown in Fig. 3.41.

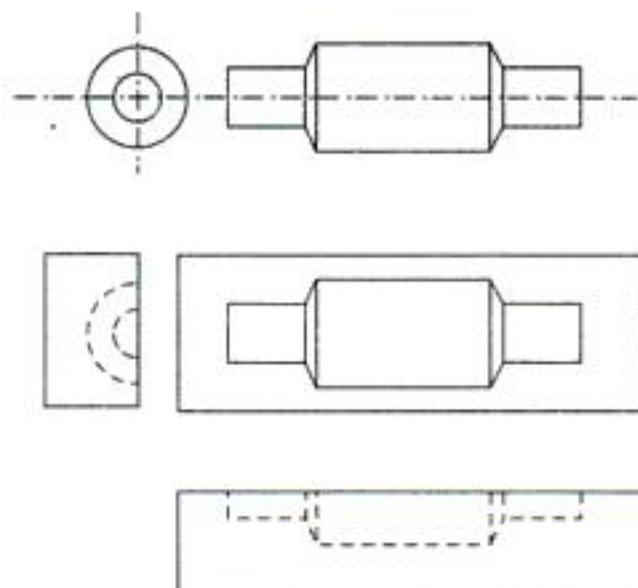


Fig. 3.41 A typical core box

If a core is symmetrical, then it can be made into two equal parts and then assembled together by adhesives or fastened by wires. The glues that are used are mixtures of talc, dextrin, flour, molasses and water. Care should be taken while applying the glue not to close the core vent holes made earlier for the gases to escape. When very large cores are to be joined, it may be necessary to use nuts and bolts. The bolt holes are generally covered with a core plug. If the core is to be mounted in a particular orientation, then some specific provision should be made in the core prints so that the core can be placed in the mould in only one position, as in Fig. 3.42.

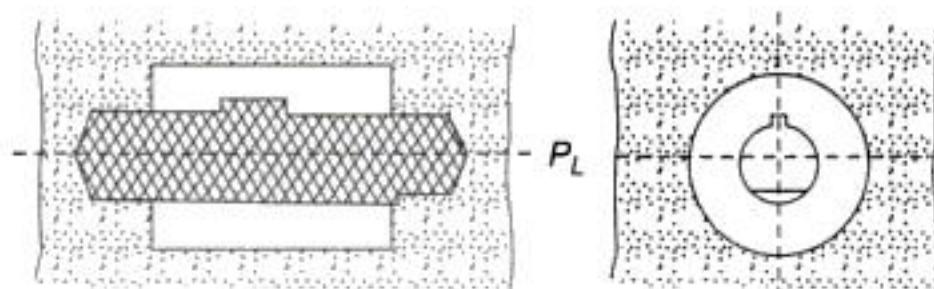


Fig. 3.42 Unsymmetrical core location

3.4.4 Core Prints

The core prints are provided so that the cores are securely and correctly positioned in the mould cavity. The design of core prints is such as to take care of the weight of the core before pouring and the upward metallo-static pressure of the molten metal after pouring. The core prints should also ensure that the core is not shifted during the entry of the metal into the mould cavity.

The main force acting on the core when metal is poured into the mould cavity, is due to buoyancy. The buoyant force can be calculated as the difference in the weight of the liquid metal to that of the core material of the same volume as that of the exposed core. It can be written as



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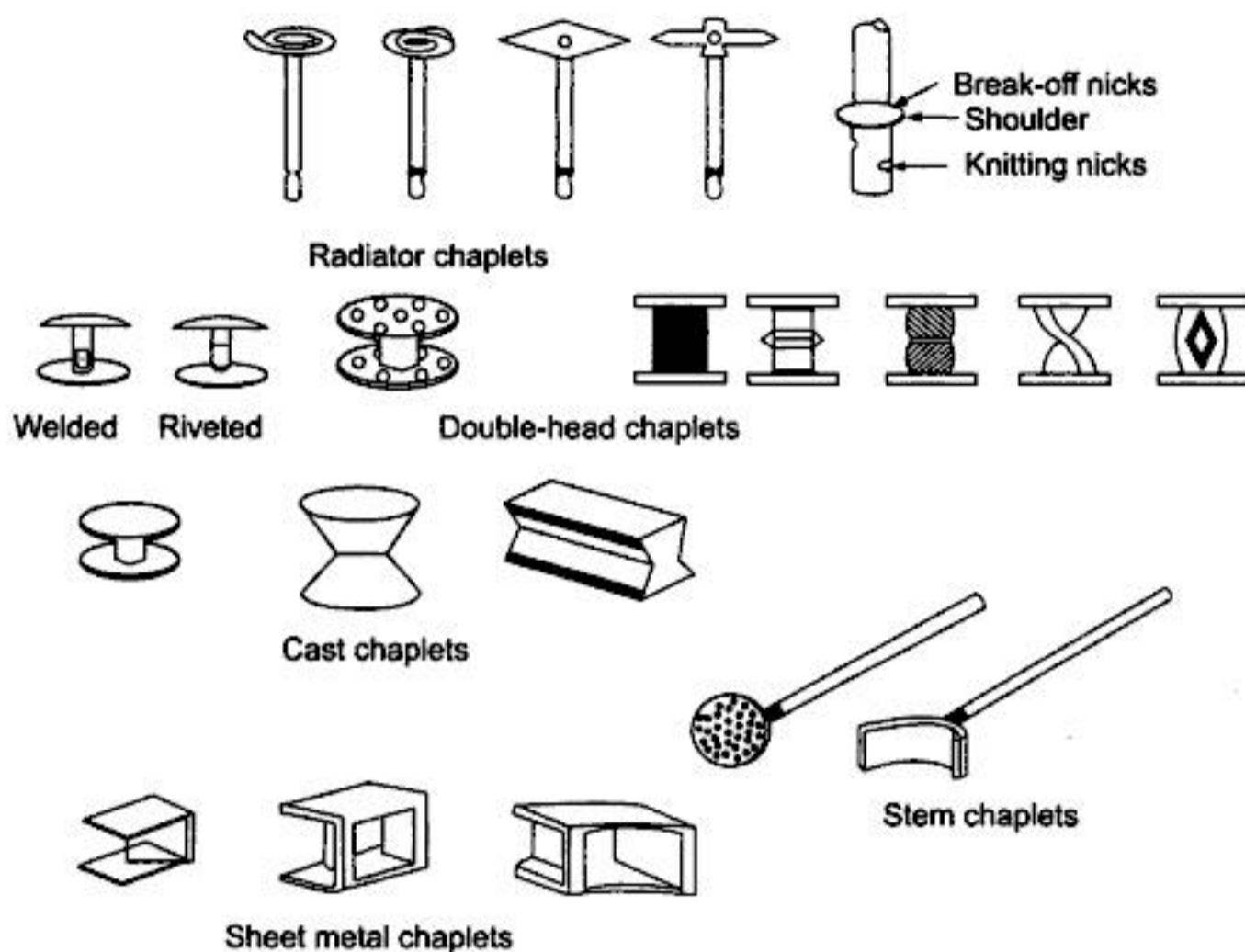


Fig. 3.47 Types of chaplets

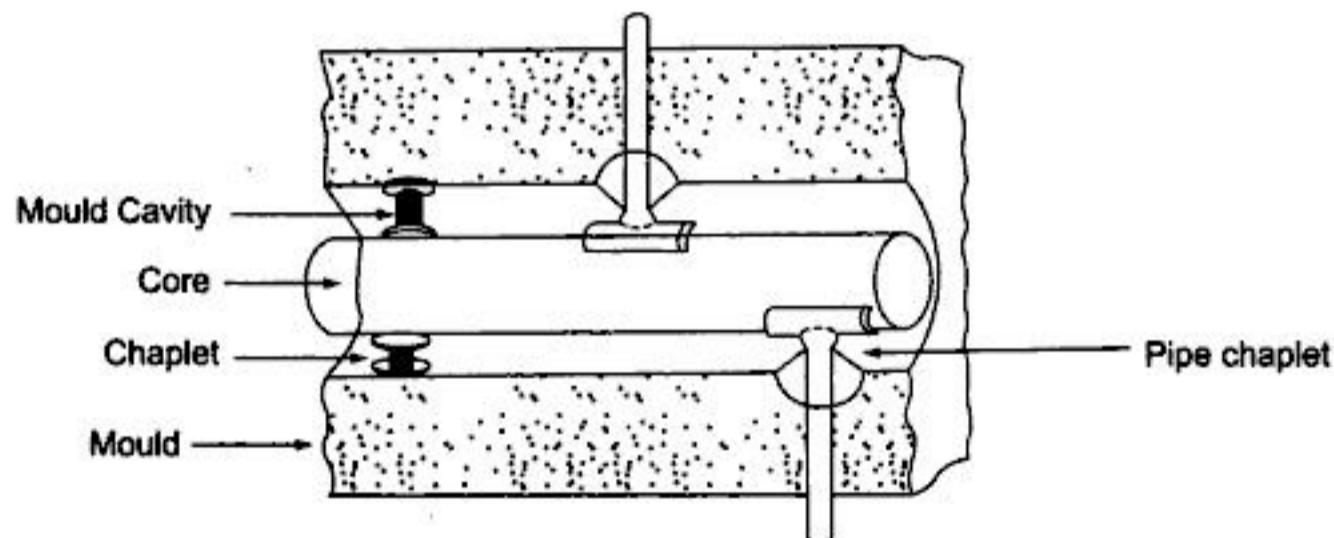


Fig. 3.48 Core supported by chaplet

If the unsupported load is less than or equal to zero, no chaplet is required. But if it is greater than zero then the chaplet area required is 29 mm^2 for every Newton of unsupported load.

3.4.6 Forces Acting on the Moulding Flasks

Earlier, the buoyancy force exerted by the core has been calculated. This force is transmitted by the core to the cope and would tend to lift the cope away from the drag. In addition to this, another force termed *metallostatic force* is also present inside the moulding cavity. This metallocostatic force is exerted by the molten metal in all the directions of the cavity. However, we are interested in the force exerted in the upward direction.



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- 3.59 Describe a method of calculating the core print dimensions.
 3.60 Briefly explain the application of chaplets.



Problems

- 3.1 A cast-iron cylinder of 450-mm outside diameter, 75-mm inside diameter, and 150 mm long is to be obtained by sand casting. Design the requisite pattern assuming that the internal hole is to be finished by machining.
- 3.2 A master aluminium pattern is to be cast using a wooden pattern for a hollow steel cylindrical piece with a flange of 50-mm width and 250-mm diameter. The cylindrical portion is 200-mm long with an outer diameter 150 mm and an inner diameter of 75 mm. If the face of the flange is to be machined, design the wooden pattern.
- 3.3 Design the patterns for the following sand-cast water pipes and specials of grey cast iron:
 a) DF pipe, Fig. 3.50
 b) DF (double flanged) 1/4 bend, Fig. 3.51
 c) All flanged tee, Fig. 3.52

In each of the above, choose the proper type of pattern and its parting line.

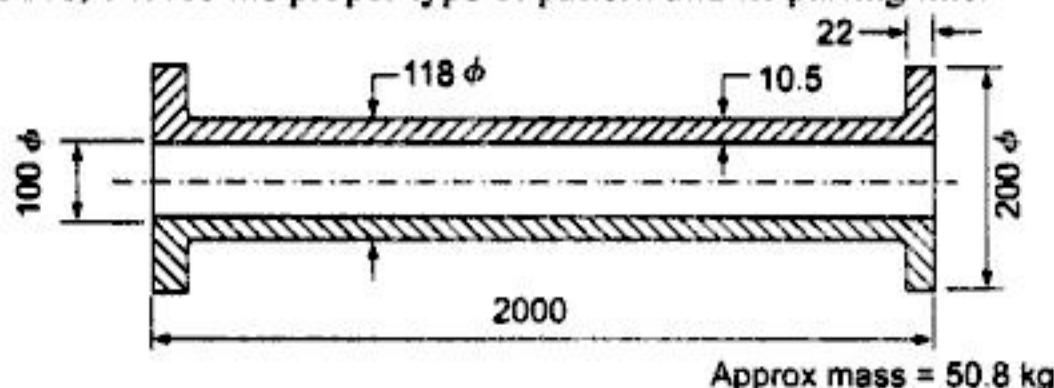


Fig. 3.50 DF pipe

- 3.4 A sample of Londha (Maharashtra) sand of 50 g is weighed after washing and drying and is found to weigh 41.6 g. What would be the clay percentage in this sand sample?
 3.5 The Bhavanagar (Gujarat) sand sample when sieved through the standard sieves was found to retain the following amounts of sand on the respective sieves.

Sieve no.	12	20	30	40	50	70	100	140	200	270	Pan
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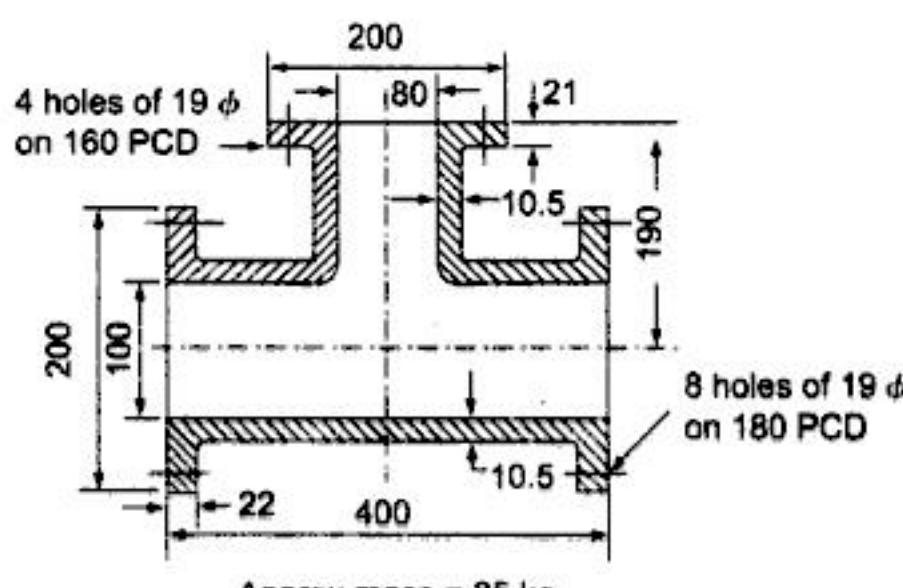


Fig. 3.51 DF 1/4 bend



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One of the walls of the pouring basin is made inclined at about 45° to the horizontal. The molten metal is poured on this face such that metal momentum is absorbed and vortex formation is avoided. In some special cases, the pouring basin may consist of partitions to allow for the trapping of the slag and maintaining constant metal height in the basin.

The main function of a pouring basin is to reduce the momentum of the liquid flowing into the mould by settling first into it. In order that the metal enters into the sprue without any turbulence, it is necessary that the pouring basin be deep enough, and also the entrance into the sprue be a smooth radius of at least 25 mm. Experience shows that the pouring basin depth of 2.5 times the sprue entrance diameter is enough for smooth metal flow and to prevent vortex formation, as shown in Fig. 4.3.

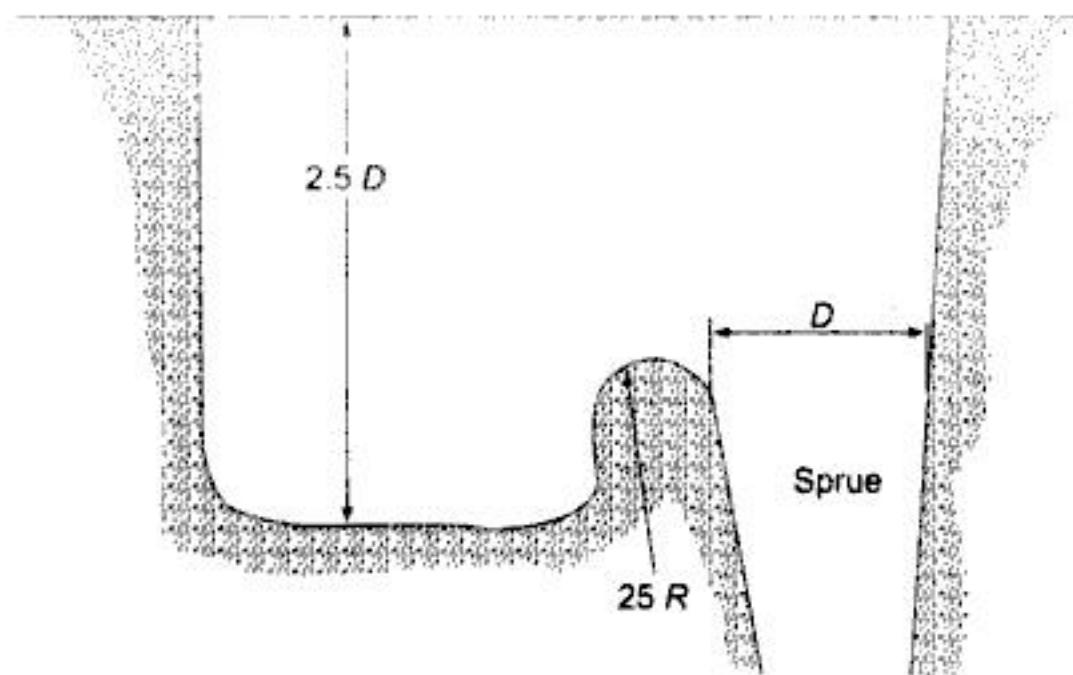


Fig. 4.3 Pouring basin proportions

In order that a vortex is not formed during pouring, it is necessary that the pouring basin be kept full. Further provision should be made in the pouring basin so that constant conditions of flow are established. This can be achieved by using a strainer core, as shown in Fig. 4.4(a). A strainer core is a ceramic-coated screen with many small holes. The strainer restricts the flow of metal into the sprue and thus helps in quick filling of the pouring basin. It helps in providing a smooth flow while restricting the flow of slag into the mould. A ceramic filter as shown in Fig. 4.4(b) completely stops slag and only clean metal is allowed to go into the sprue and also ensures a constant flow of metal.

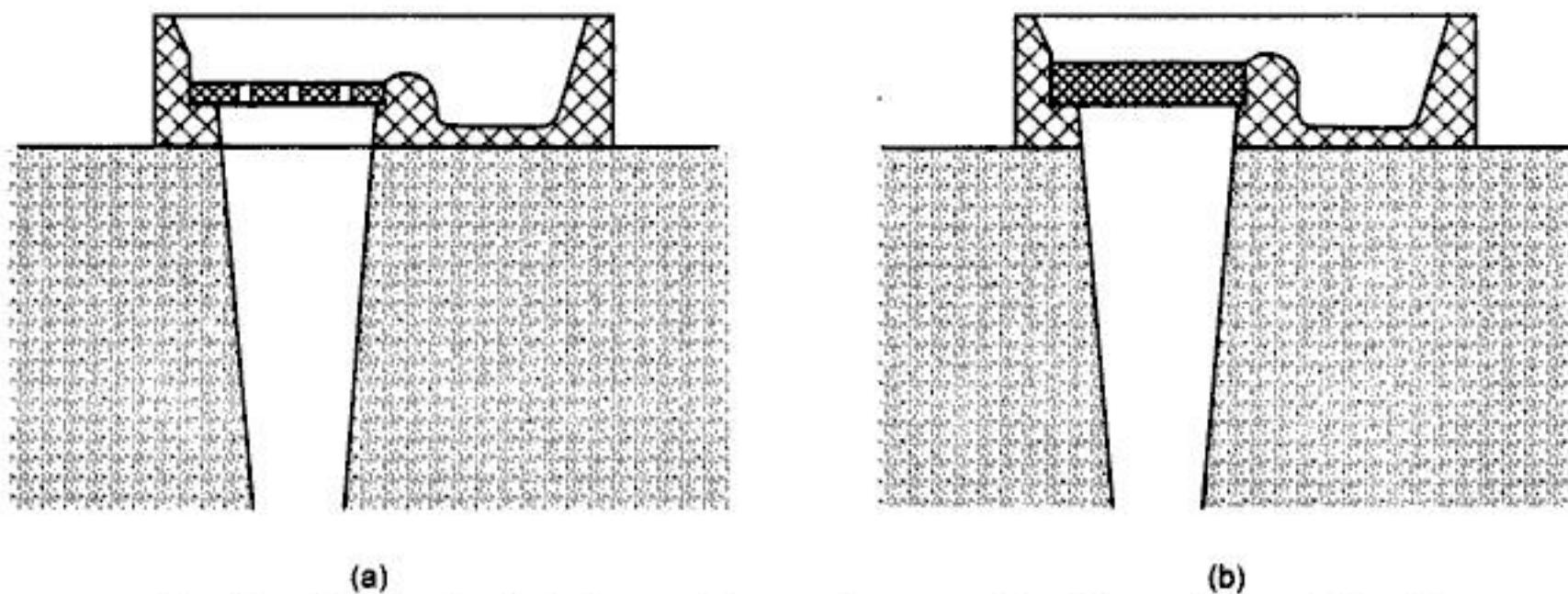


Fig. 4.4 Pouring basin designs with a strainer core, (a) and ceramic foam filter (b)



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those materials, which are likely to form excessive dross. It is not suggested for nonferrous materials and is suggested only for ferrous alloys. It is suitable only for simple casting shapes, which are essentially shallow in nature. To reduce the mould erosion, pencil gates (Fig. 4.9(a)) are provided in the pouring cup. This type of gate requires minimum of additional runners to lead the liquid metal into the cavity, and as such, provides higher casting yield. Capabilities of top gating system are significantly extended by using direct-pour, top-gating system incorporating insulating sleeve with ceramic foam filter as shown in Fig. 4.9(b).

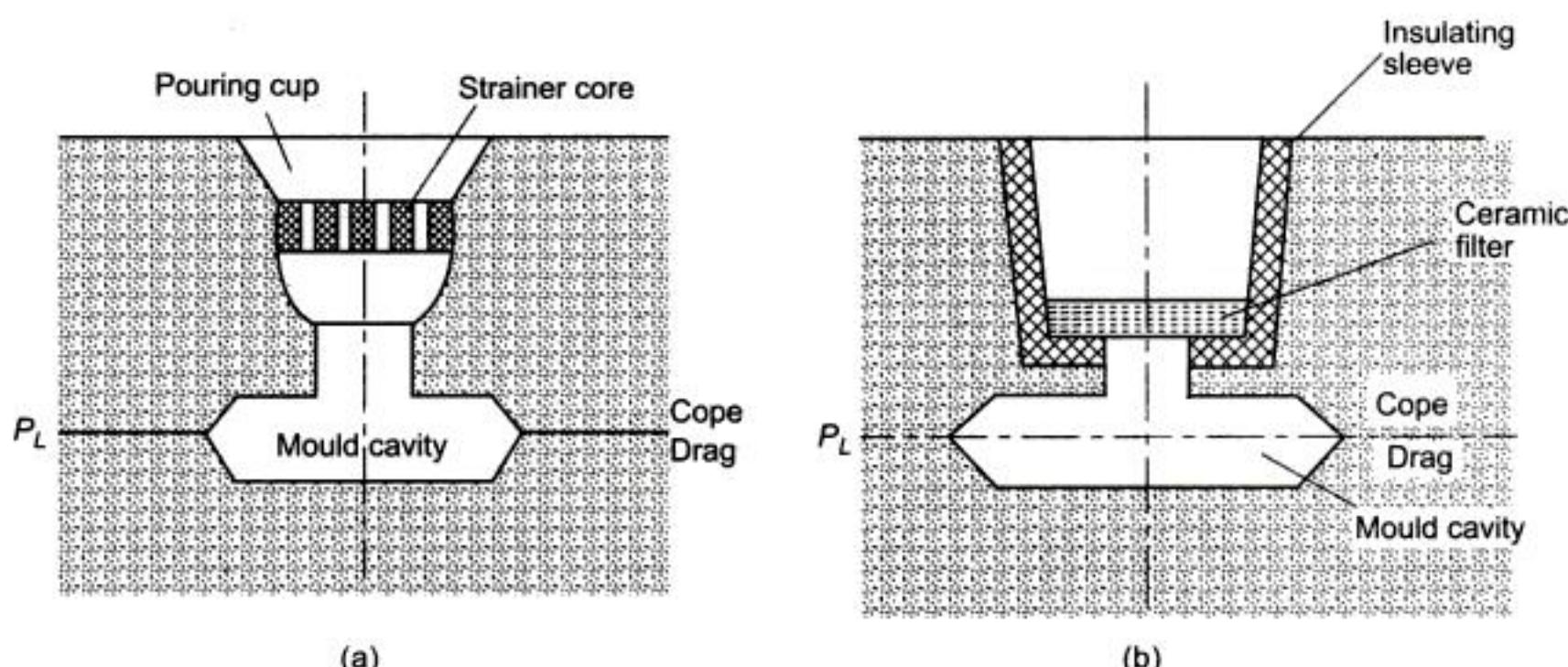


Fig. 4.9 Top gate

Bottom Gate When molten metal enters the mould cavity slowly as shown in Fig. 4.10, it would not cause any mould erosion. Bottom gate is generally used for very deep moulds. It takes somewhat higher time for filling of the mould. These gates may cause unfavourable temperature gradients compared to the top gating. Thus, the system may have to use additional padding of sections towards risers and large riser sizes to compensate for the unfavourable temperature distribution. Bottom gating may sometimes be preferable in conjunction with the use of side risers since the metal enters the riser directly without going through the mould cavity.

Parting Gate This is the most widely used gate in sand castings. As the name implies, the metal enters the mould at the parting plane when a part of the casting is in the cope and a part in the drag as in Fig. 4.11. For the mould cavity in the drag, it is a top gate and for the cavity in the cope it is a bottom gate. Thus, this type of gating tries to derive the best of both the types of gates, viz, top and bottom gates. Of all the gates, this is also the easiest and most economical in preparation. However, if the drag portion of the mould cavity is deep, it is likely to cause mould erosion and aggravate dross formation and air entrapment in the case of nonferrous alloys. This can be somewhat reduced by making the gate area large such that the liquid metal velocity is minimized and it flows slowly along the walls into the mould cavity.

Step Gate Such gates are used for heavy and large castings. The molten metal enters (Fig. 4.12) mould cavity through a number of in-gates, which are arranged in vertical steps. The size of ingates are normally increased from top to bottom such that the metal enters the mould cavity from the bottom-most gate and then progressively moves to the higher gates. This ensures a gradual filling of the mould without any mould erosion and produces a sound casting.



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a part of the casting which is heavy, a chill is placed close to it as shown in Fig. 4.14, so that more heat is quickly absorbed by the chill from the larger mass making the cooling rate equal to that of the thin sections. Thus, this does not permit the formation of a shrinkage cavity. But use of a chill means essentially providing higher cooling rate which is also likely to form a hard spot at the contact area with the chill and may therefore cause a problem if that areas need further processing by way of machining.

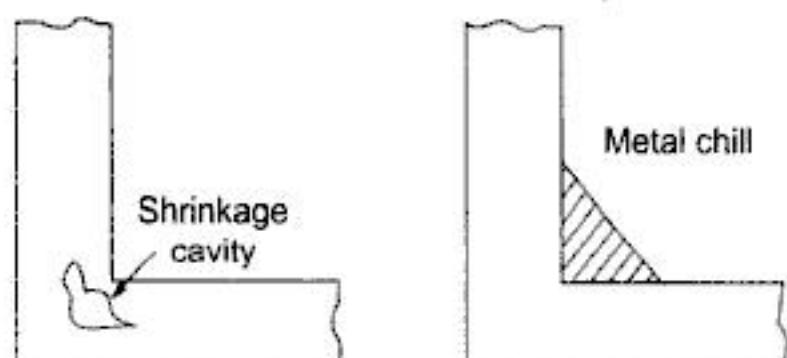


Fig. 4.14 Chill

4.1.3 Casting Yield

All the metal that is used while pouring is not finally ending up as a casting. Typical routes the metal would take in a foundry are shown in Fig. 4.15. There will be some losses in the melting. Also there is a possibility that some castings may be rejected because of the presence of various defects. On completion of the casting process, the gating system used is removed from the solidified casting and remelted to be used again as raw material. Hence, the casting yield is the proportion of the actual casting mass, W , to the mass of metal poured into the mould, w , expressed as a percentage as follows.

$$\text{Casting yield} = \frac{W}{w} \times 100$$

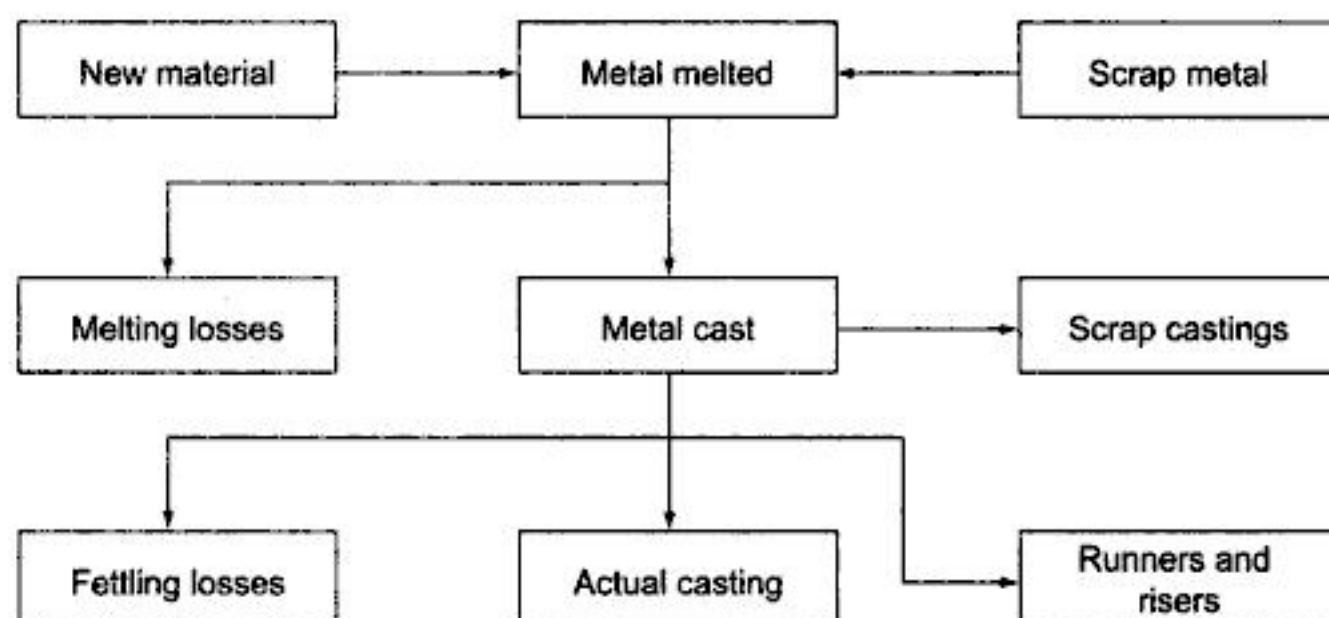


Fig. 4.15 Utilization of the metal in the foundry

The higher the casting yield, the higher is the economics of the foundry practice. It is therefore desirable to give consideration to maximising the casting yield, at the design stage itself.

Casting yield depends to a great extent on the casting materials and the complexity of the shape. Generally, those materials which shrink heavily have lower casting yields. Also, massive and simple shapes have higher casting yield compared to small and complex parts. Typical casting yields are presented in Table 4.3 as a guide.



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Typical pouring rates used for different casting alloys are given in Table 4.4. The calculated values from any of the above formulae may be checked from the Table 4.4.

Table 4.4 Typical pouring rates for sand castings

Metal	Pouring rate in kg/s for castings of mass, kg			
	Up to 10	10–50	50–100	100–500
Pig iron	1.1	1.5–2.0	3.0–4.0	3.5–6.0
Steel	1.2–1.4	1.9–2.5	4.0–5.0	4.5–7.0
Aluminium alloys	0.25–0.3	0.5–0.7	1.0–1.3	1.2–2.0

|| Example 4.1 || Calculate the optimum pouring time for a casting whose mass is 20 kg and having an average section thickness of 15 mm. The materials of the casting are grey cast iron and steel. Take the fluidity of iron as 28 inches.

Gray cast iron

$$\begin{aligned}\text{Pouring time, } t &= K \left(1.41 + \frac{T}{14.59} \right) \sqrt{W} \text{ s} \\ &= \frac{28}{40} \left(1.41 + \frac{15}{14.59} \right) \sqrt{20} = 7.632 \text{ s}\end{aligned}$$

Steel

$$\begin{aligned}\text{Pouring time, } t &= (2.4335 - 0.3953 \log W) \sqrt{W} \text{ s} \\ &= (2.4335 - 0.3953 \log 20) \sqrt{20} = 8.5825 \text{ s}\end{aligned}$$

|| Example 4.2 || Calculate the optimum pouring time for a casting whose mass is 100 kg and a thickness of 25 mm. Fluidity of iron is 32 inches. Calculate both for cast iron and steel.

Grey cast iron

$$\text{Pouring time, } t = \frac{32}{40} \left(1.41 + \frac{25}{14.59} \right) \sqrt{100} = 24.988 \text{ s}$$

Steel

$$\text{Pouring time, } t = (2.4335 - 0.3953 \log 100) \sqrt{100} = 16.429 \text{ s}$$

4.2.2 Choke Area

Having calculated the optimum pouring time, it is now required to establish the main control area which meters the metal flow into the mould cavity so that the mould is completely filled within the calculated pouring time. This controlling area is called choke area. Normally the choke area happens to be at the bottom of the sprue and hence the first element to be designed in the gating system is the sprue size and its proportions. The main advantage in having sprue bottom as the choke area is that proper flow characteristics are established early in the mould.

The choke area can be calculated using Bernoulli's equation as

$$A = \frac{W}{d t C \sqrt{2 g H}}$$



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Assuming a composition factor of 4.0 and a pouring temperature of 1300°C, the fluidity, obtained from Fig. 3.32, is 22 inches.

$$\text{Pouring time, } t = \frac{22}{40} \left(1.41 + \frac{50}{14.59} \right) \sqrt{49.125} = 18.646 \text{ s} \approx 19 \text{ s}$$

Calculate effective sprue height. Assuming a top gating system with 100 mm cope height, Effective sprue height = 100 mm (Fig. 5.21)

Select efficiency factor C from Table 4.6, assuming that gating system is pressurized and consists of two runners with four in-gates; $C = 0.73$

Assuming the density of the liquid metal = $6.90 \times 10^4 \text{ kg/mm}^3$

$$\text{Choke area, } A = \frac{49.125}{6.90 \times 10^4 \times 19 \times 0.73 \sqrt{2 \times 9800 \times 100}} = 366.648 \text{ mm}^2$$

In a pressurized gating system, the choke is located in in-gates, with four ingates, the in-gate area of each is 90 mm^2 . Assuming rectangular cross sections for in-gates, the ingate dimensions would be $15 \times 6 \text{ mm}$.

4.2.3 Gating Ratios

The gating ratio refers to the proportion of the cross sectional areas between the sprue, runner and in-gates and is generally denoted as sprue area:runner area:in-gate area. Depending on the choke area, there can be two types of gating systems:

Non-pressurized

Pressurized

A non-pressurized gating system having choke at the bottom of the sprue base, having total runner area and in-gate areas higher than the sprue area. In this system there is no pressure existing in the metal flow system and thus it helps to reduce turbulence. This is particularly useful for casting drossy alloys such as aluminium and magnesium alloys. These have tapered sprues, sprue base wells and pouring basins. When the metal is to enter the mould cavity through multiple in-gates, the cross section of the runner should accordingly be reduced at each of a runner break-up to allow for equal distribution of metal through all the in-gates. The gating ratio of a typical example is

Sprue:runner:in-gate :: 1:4:4

The disadvantages of unpressurized gating are the following:

The gating system needs to be carefully designed to see that all parts flow full. Otherwise some elements of the gating system may flow partially allowing for air aspiration. Tapered sprues are invariably used with an unpressurized system. Also, the runners are maintained in drag while the gates are kept in cope to ensure that the runners are full. Casting yield gets reduced because of the large metal involved in the runners and gates.

In the case of a pressurized gating system, normally the in-gate area is the smallest, thus maintaining a back pressure throughout the gating system. Because of this back pressure in the gating system, the metal is more turbulent and generally flows full and thereby, can minimize the air aspiration even when a straight sprue is used (after the initial stages of pouring). When multiple gates are used, this system allows all the gates to flow full. These systems generally provide a higher casting yield since the volume of metal used up



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|| Example 4.4 || Calculate the gating requirements for the casting shown in Fig. 4.21 to be cast in C30 steel.

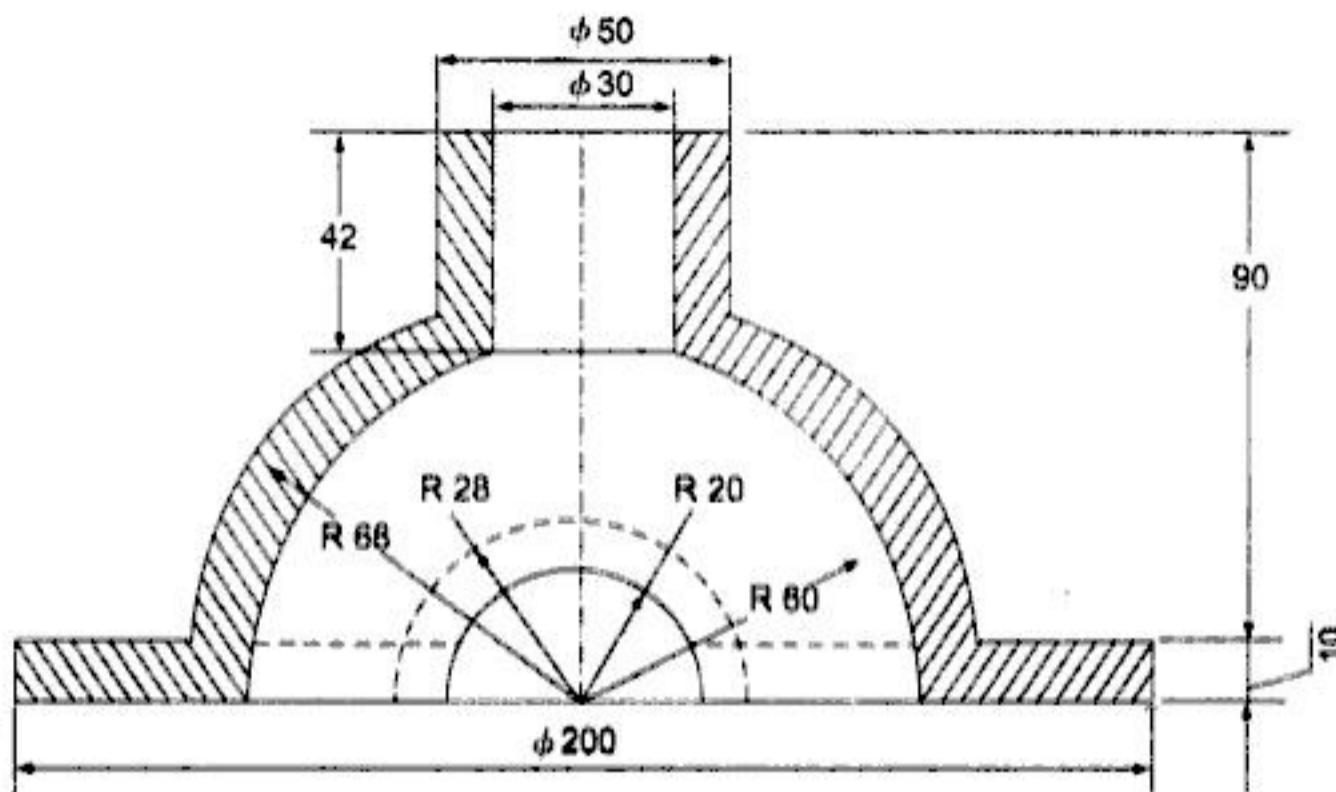


Fig. 4.21

Calculate the volume of the casting as a sum of hemisphere, cylinder and flange volumes:

$$\text{Hemisphere} = \frac{4}{3} \times \frac{\pi}{2} (68^2 - 60^2) = 206\,156 \text{ mm}^3$$

$$\text{Top cylinder} = \frac{\pi}{4} (58^2 - 30^2) \cdot 42 = 81\,279 \text{ mm}^3$$

$$\text{Flange} = \frac{\pi}{4} (200^2 - 120^2) 10 = 201\,062 \text{ mm}^3$$

$$\text{Total volume} = 206\,156 + 201\,062 + 81\,279 = 488\,497 \text{ mm}^3$$

$$\text{Mass of the casting} = 488\,497 \times 7.86 \times 10^{-6} = 3.84 \text{ kg}$$

$$\text{There are two castings in the mold and their weight } 3.84 \times 2 = 7.68 \text{ kg}$$

$$\text{Weight of metal poured} = \frac{2 \times 3.84}{0.60} = 12.8 \text{ kg} \quad (\text{Assuming a casting yield of 0.60})$$

$$\text{Pouring time} = (2.4335 - 0.3953 \cdot \log 12.80) \sqrt{12.80} = 7.14 \text{ s}$$

$$\text{Pouring rate} = \frac{12.8}{7.14} = 1.793 \text{ kg/s}$$



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When height-to-diameter ratio of the riser is equal to 1

$$\text{LM4: } X = \frac{33.45}{23.98 - Y}$$

$$\text{LM11: } X = \frac{17.11}{12.58 - Y}$$

When height-to-diameter ratio of the riser is equal to 1.5

$$\text{LM4: } X = \frac{32.09}{23.98 - Y}$$

$$\text{LM11: } X = \frac{16.75}{12.58 - Y}$$

For nodular iron in CO₂ moulds, the following equation may be used.

$$X = \frac{39.44}{27.78 - Y}$$

The above equation when plotted will be as shown in Fig. 4.24. The line shows the locus of the points that separate the sound castings and castings with shrinkages in steel castings.

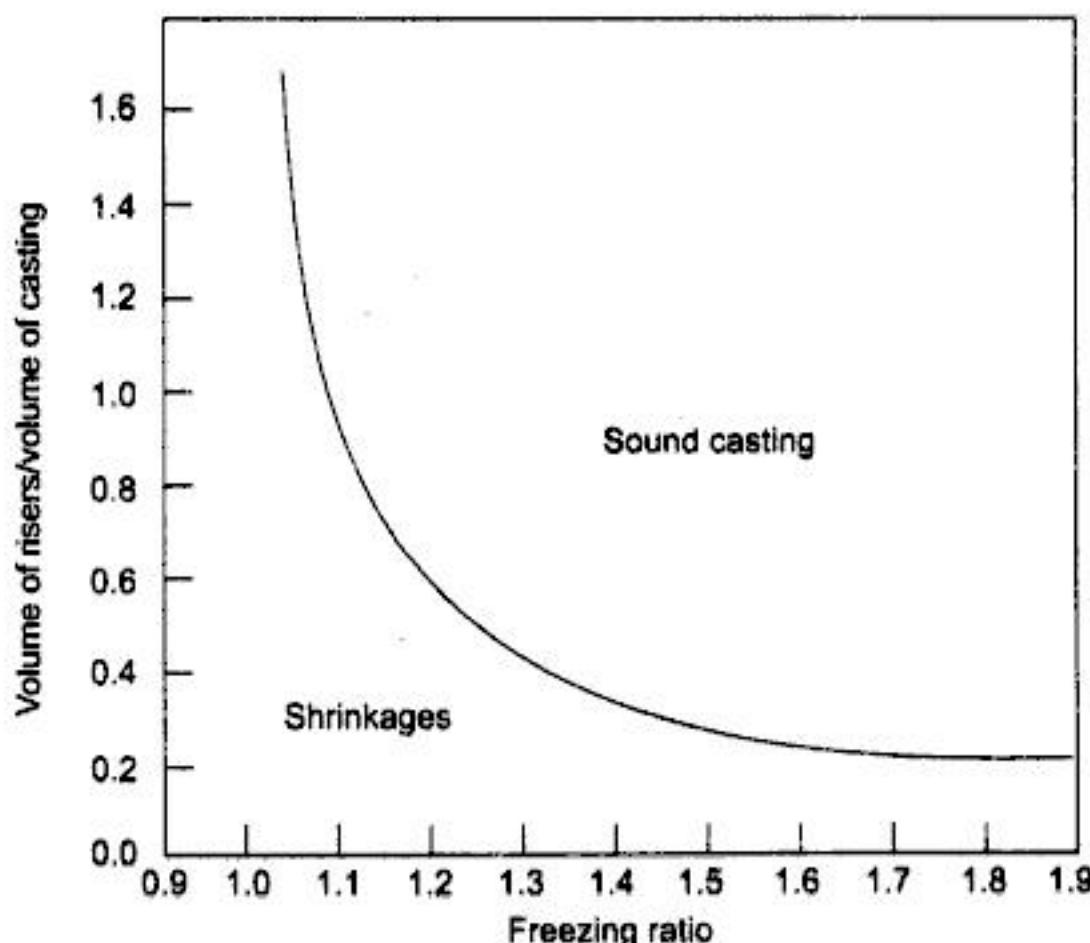


Fig. 4.24 Caine's equation

Example 4.5 Calculate the size of a cylindrical riser (height and diameter equal) necessary to feed a steel slab casting of dimensions 25 × 25 × 5 cm with a side riser, casting poured horizontally into the mould.



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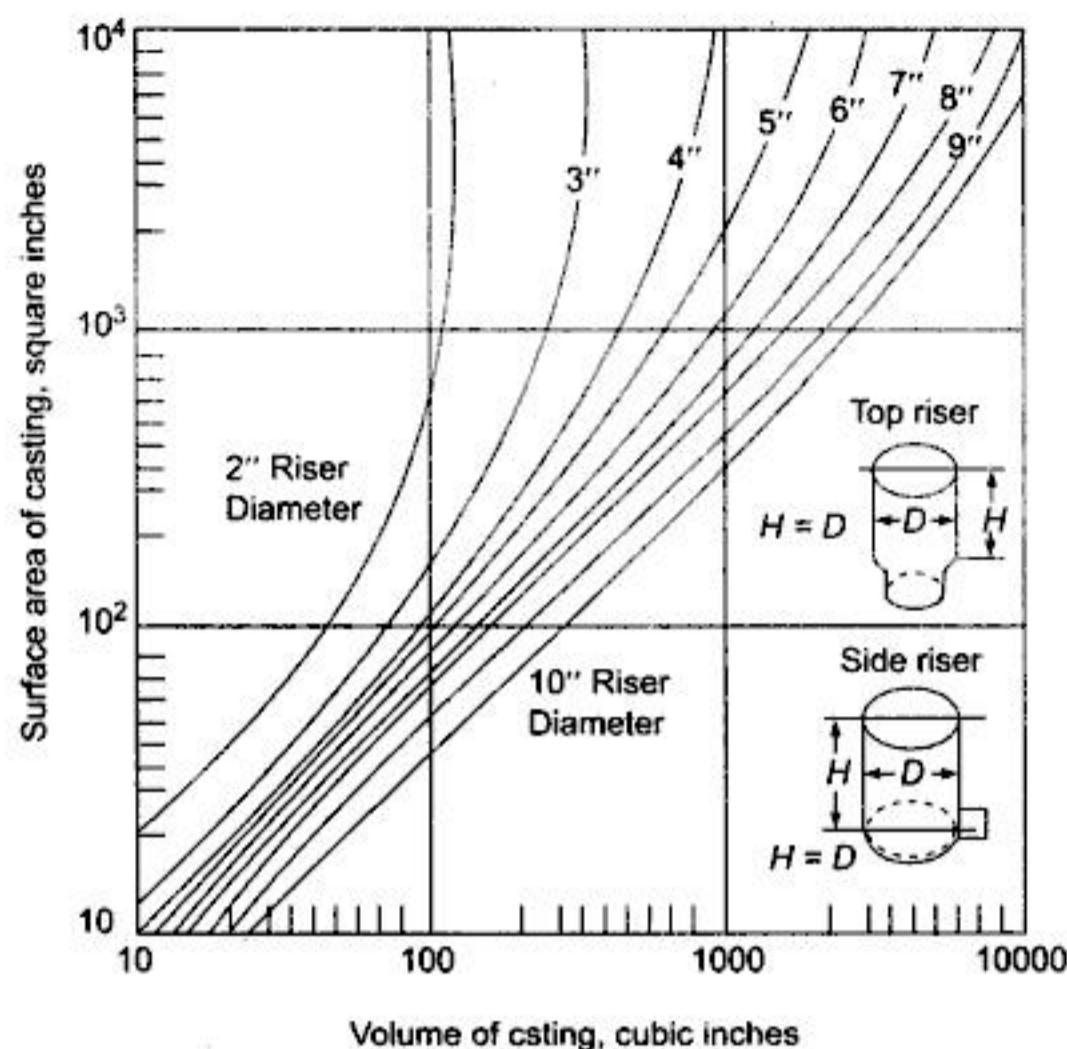


Fig. 4.30 Risering curves for grey cast iron in green sand moulds

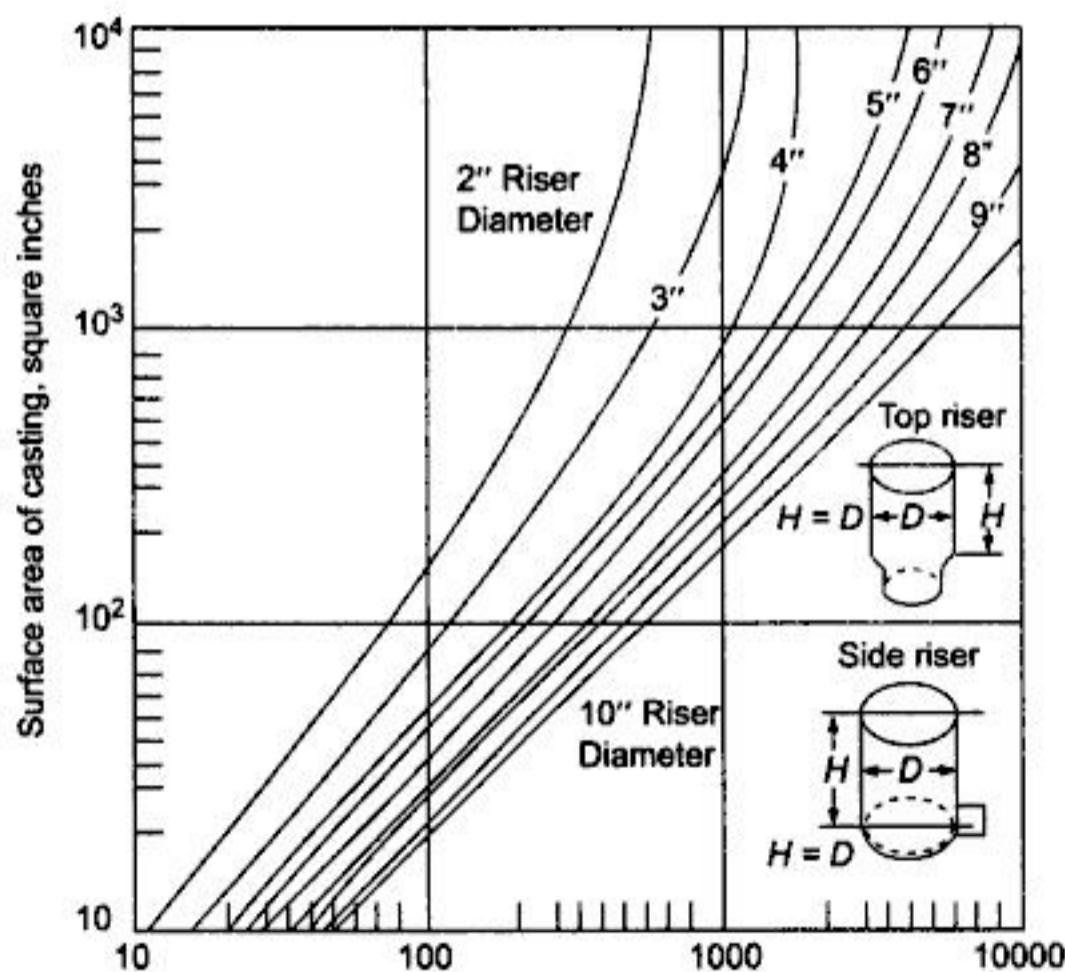


Fig. 4.31 Risering curves for grey cast iron in dry sand moulds

grey cast iron (3.5% C; 2.2% Si) may not require any risering. If any doubt persists then a small shrink bob of 2 to 4 % of casting volume may be provided at the necessary point.



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variation in the moulding practice, it is possible to reduce the risering requirement as shown in Fig. 4.35(c) as the heat from the castings would keep the metal hot in the riser for a longer period.

4.3.5 Feeding Aids

To increase the efficiency of a riser, it is necessary to keep the metal in the riser in liquid form for as long a period as required so that it would feed the casting till it solidifies. When this is done, the riser volume decreases, resulting in a higher yield. The aids used for this purpose are called *feeding aids*. They can be either exothermic materials or insulators.

Exothermic materials when added at the top of the riser would give out heat and also act as heat insulators (through the reaction products) to the atmosphere, thus reducing the heat loss through radiation. The exothermic materials that can be used are graphite or charcoal powder, rice hulls and thermit mixtures. The carbonaceous materials called *anti-piping compounds*, besides being cheap, provide insulation and also get oxidised slowly. But thermit mixtures get oxidised very quickly and release heat over a very small period and subsequently, the effect would be that of only the residue acting as an insulator. As such, these are not generally used.

For steel casting, an insulating shield on the top of an open riser is very effective since it reduces a considerable amount of heat loss by radiation. Loose cellulose material such as rice husk is used as top insulation. For example, the solidification time of a 100×100 mm cylindrical riser for steels increases from 5 minutes to 13.4 minutes, while for aluminium, the same changes from 12.3 to 14.3 minutes. Thus, for steels this is the important way in decreasing the size of the riser.

Alternately, riser sleeves which are either purely insulating or mildly exothermic may be used to reduce the heat transfer through the walls of the riser and thus improve the feeding of the castings. These are generally made of fire clay-saw dust for ferrous materials. These are fired before use to burnout the saw dust and leave air cells. Plaster of Paris is generally used as insulator for nonferrous materials, though it cannot be used for ferrous materials because of the possibility of sulphur pick-up by the molten metal in the riser. For example, the solidification time of a 100×100 mm cylindrical riser with insulating sleeve for steels increases from 7.5 minutes to 43 minutes, while for aluminium the same changes from 31.1 to 45.6 minutes. Thus, an optimum combination of insulating sleeves around the cylindrical riser along with the top insulating shield would be useful for all casting metals.

Since the feeding aids keep the metal in liquid form in the riser for longer periods, the modulus of the riser needs to be reduced as compared to the conventional practice. This can be done by introducing a factor f , called *modulus extension factor* (MEF), which represents the increase in the modulus of the riser. Thus,

$$M_r = \frac{1.2}{f} M_c$$

The implicit assumption in the above equation is that the insulation effect at the sides and the top are same. If not, for example, in the case of top risers, proper care needs to be taken to get an average value of f .

In order to get the proper size of the riser, it is necessary to get the correct value of the factor f , which is difficult to obtain since a large number of proprietary sleeves are available. Typical values could be 1.8 for



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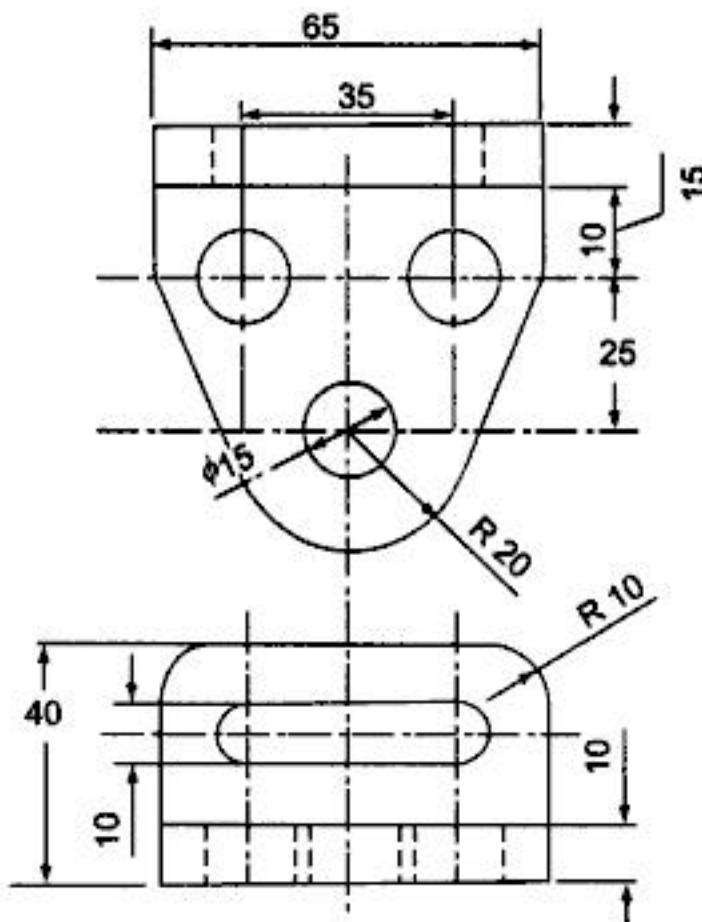


Fig. 4.37 Pattern Example 1

at each stage the choice of parameters and values chosen. Give the details of sand mould with dimensions and the arrangement of gating elements.

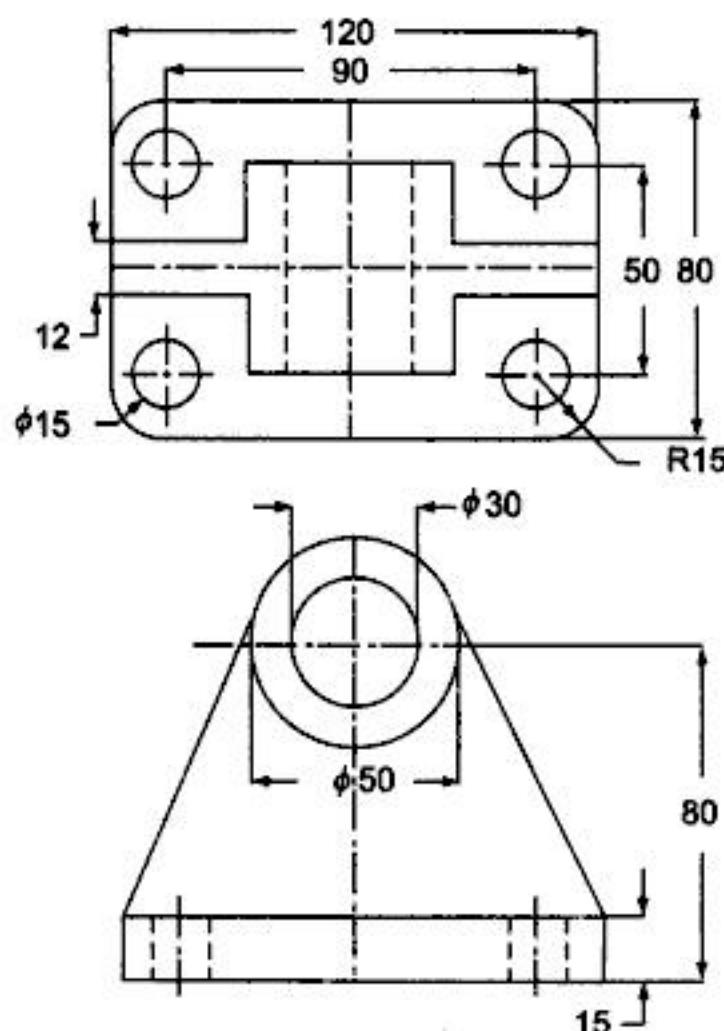


Fig. 4.38 Pattern Example 2



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charge, flux and coke are alternately fed into the cupola through the charge door maintaining the necessary proportions and rate of charging. The charge is then allowed to soak in the heat for a while, and then the air blast is turned on. Within about 5 to 10 minutes, the molten metal is collected near the tap hole. When enough molten metal is collected in the well of the cupola, the slag is drained off through the slag hole before opening the tap hole. The molten metal is collected in the ladles and then transported to the moulds into which it is poured with a minimum time loss.

The charge needed to produce cast iron, essentially consists of pig iron, cast iron scrap and steel scrap when alloy cast iron is needed. The proportions of these depend on their chemical compositions and on the final chemical composition of cast iron desired.

The fluxes are added in the charge to remove the oxides and other impurities present in the metal. The flux most commonly used is limestone (CaCO_3) in a proportion of about 2 to 4% of the metal charge. Some of the other fluxes that may also be used are dolomite, sodium carbonate and calcium carbide. The flux is expected to react with the oxides and form compounds which have low melting point and are also lighter. As a result, the molten slag tends to float on the metal pool and thus, can very easily be separated. Typical operation characteristics of cupola are presented in Table 5.1.

A variation of the cupola is called *hot blast cupola*. In this, the air supply is pre-heated to a temperature of 200 to 400 °C with the help of the hot gases coming out of the stack or by a separate heat input. In either case, the equipment gets complicated by the addition of the extra pre-heaters and the air circulation equipment. The main advantage gained is that the amount of heat required by the cupola gets reduced. This in turn, reduces the contact of the metal with the coke and air thus reducing the carbon and sulphur pickups as well as the oxidation losses. Because of the additional equipment and the extra care needed for operation, the hot blast cupolas are used only in shops that require large amounts of metal to be melt in a continuous basis.

5.1.2 Charge Calculations

It is very important in the foundry to know the final composition of the metal being obtained, so as to control it properly. The elements in the final analysis are essentially the sum total of what is contained in each of the charge ingredients, with some losses or pick-up in the cupola. Out of the various elements, the ones that are relevant are carbon, silicon, manganese and sulphur.

As the charge comes through the coke bed, some amount of carbon is picked up by the metal depending on the temperature and the time when the metal is in contact with the coke. However, it may be reasonable to assume a pick-up of the order of 0.15% carbon.

Silicon is likely to get oxidised in the cupola and therefore, a loss of 10% of total silicon contained in the charge is normal. Under the worst conditions, it may go as high as 30%. If the silicon content in the charge is not high, extra silicon can be added by inoculating the metal in the ladle with ferrosilicon.

Manganese is also likely to be lost in the melting process. The loss could be of the order of 15 to 20%. Loss of manganese in the final analysis can be made up by the addition of ferromanganese.

Similar to carbon, sulphur is also likely to be picked up from coke during melting. The pick-up depends on the sulphur content of the coke, but a reasonable estimate could be 0.03 to 0.05%.

Examples are presented below for estimating the final analysis of the melt.

Example 5.1 Estimate the final composition of the cast iron produced with the following charge compositions and proportions.



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Example 5.2

Charge materials	kg	%	Carbon, % in material	in charge	Silicon, % in material	in charge	Manganese, % in material	in charge	Sulfur, % in charge
Pig iron 1	300	30	3.5	$3.5 \times 0.30 = 1.05$	3	$3.0 \times 0.30 = 0.90$	1	$1.0 \times 0.30 = 0.30$	0.02 = 0.006
Pig iron 3	300	30	3.5	$3.5 \times 0.30 = 1.05$	2.5	$2.5 \times 0.30 = 0.75$	0.8	$0.80 \times 0.30 = 0.24$	0.02 = 0.006
Scrap 1	400	40	3.5	$3.5 \times 0.40 = 1.40$	1.8	$1.8 \times 0.40 = 0.72$	0.6	$0.60 \times 0.40 = 0.24$	0.08 = 0.032
Total	1000	100			3.5		2.37		0.044
Total in charge, %					+0.15		-0.237		+0.05
Change in cupola					3.65		2.133		0.624
Estimated composition, %									0.094
Required composition, %					3.2 to 3.6		2.3 to 2.6		0.6 to 0.8 0.08 max



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In the electric furnaces the resistance-type heating is generally used for holding furnaces to maintain the liquid metal at a certain temperature for nonferrous alloys such as for diecasting. However, the electric furnaces in view of their high degree of temperature control and flexibility of operation have been widely used for melting for small to medium-sized castings in ferrous as well as nonferrous alloys.

Electric Arc Furnace For heavy steel castings, the open-hearth type of furnaces with electric arc or oil fired would be generally suitable in view of the large heat required for melting. Electric arc furnaces are more suitable for ferrous materials and are larger in capacity. This type of furnace draws an electric arc that rapidly heats and melts the charge material as shown in Fig. 5.2. The bowl-shaped bottom of the furnace, called the hearth, is lined with refractory bricks and granular refractory material. Heat is directly transferred to the charge metal from the electrode arc. The furnace has a tilting mechanism allowing it to be tilted forward for metal tapping or backward for deslagging. Once the melt is ready to pour, the electrodes are raised through the roof and the furnace is tilted to pour the molten metal into a receiving ladle.

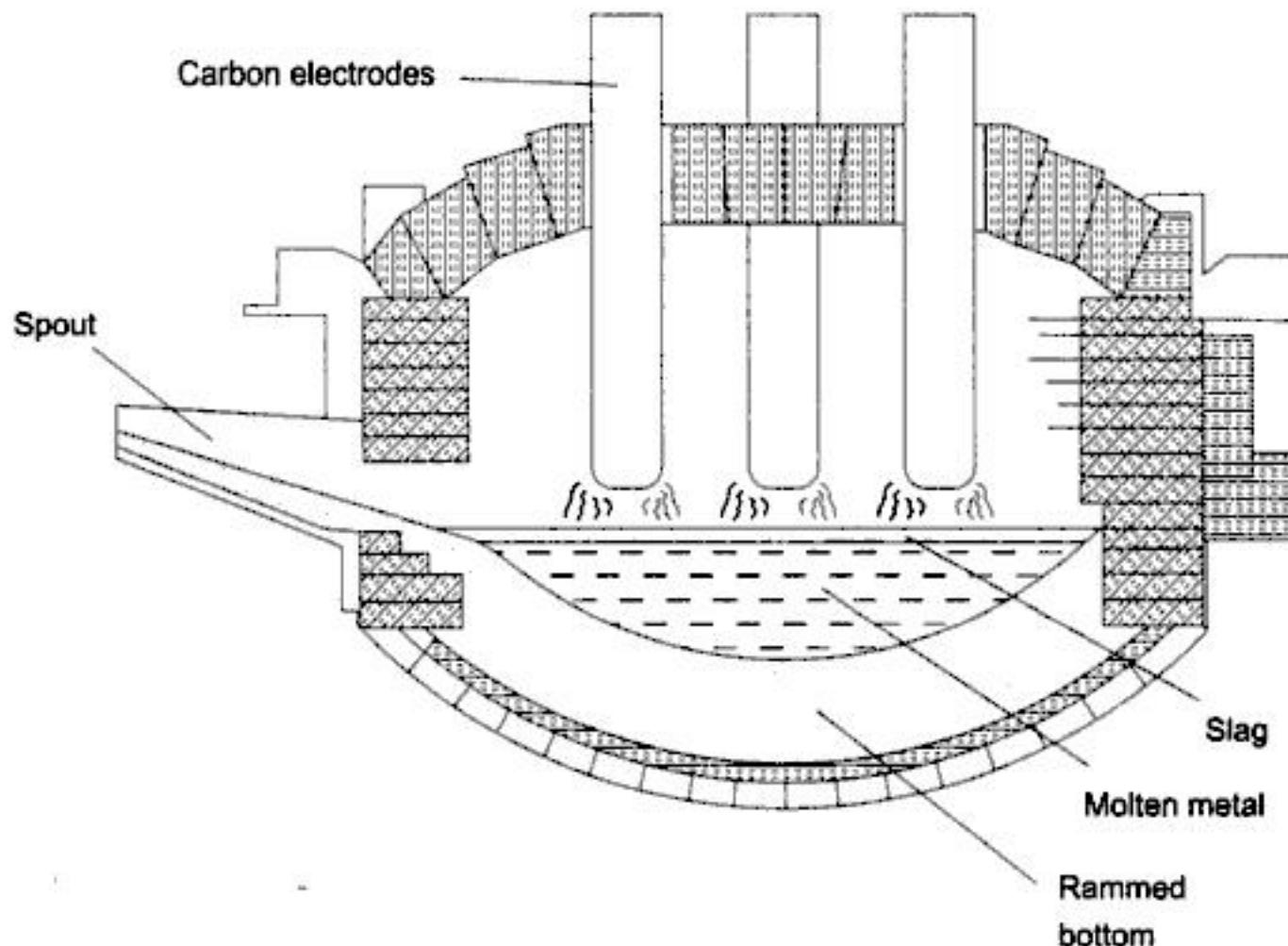


Fig. 5.2 Cross section of an Electric arc furnace

Crucible Furnace Smaller foundries generally prefer the crucible furnace. The crucible is generally heated by electric resistance or gas flame. In these, the metal is placed in a crucible of refractory metal and the heating is done to the crucible—thus there is no direct contact between the flame and the metal charge. This type of melting is very flexible since it suits a variety of casting alloys. Degassing and any metal treatment can be completed in the crucible before it is removed for pouring. Melt quality and temperature can also be controlled reasonably well.

Induction Furnace The induction furnaces are used for all types of materials, the chief advantage being that the heat source is isolated from the charge and the slag and flux get the necessary heat directly from the



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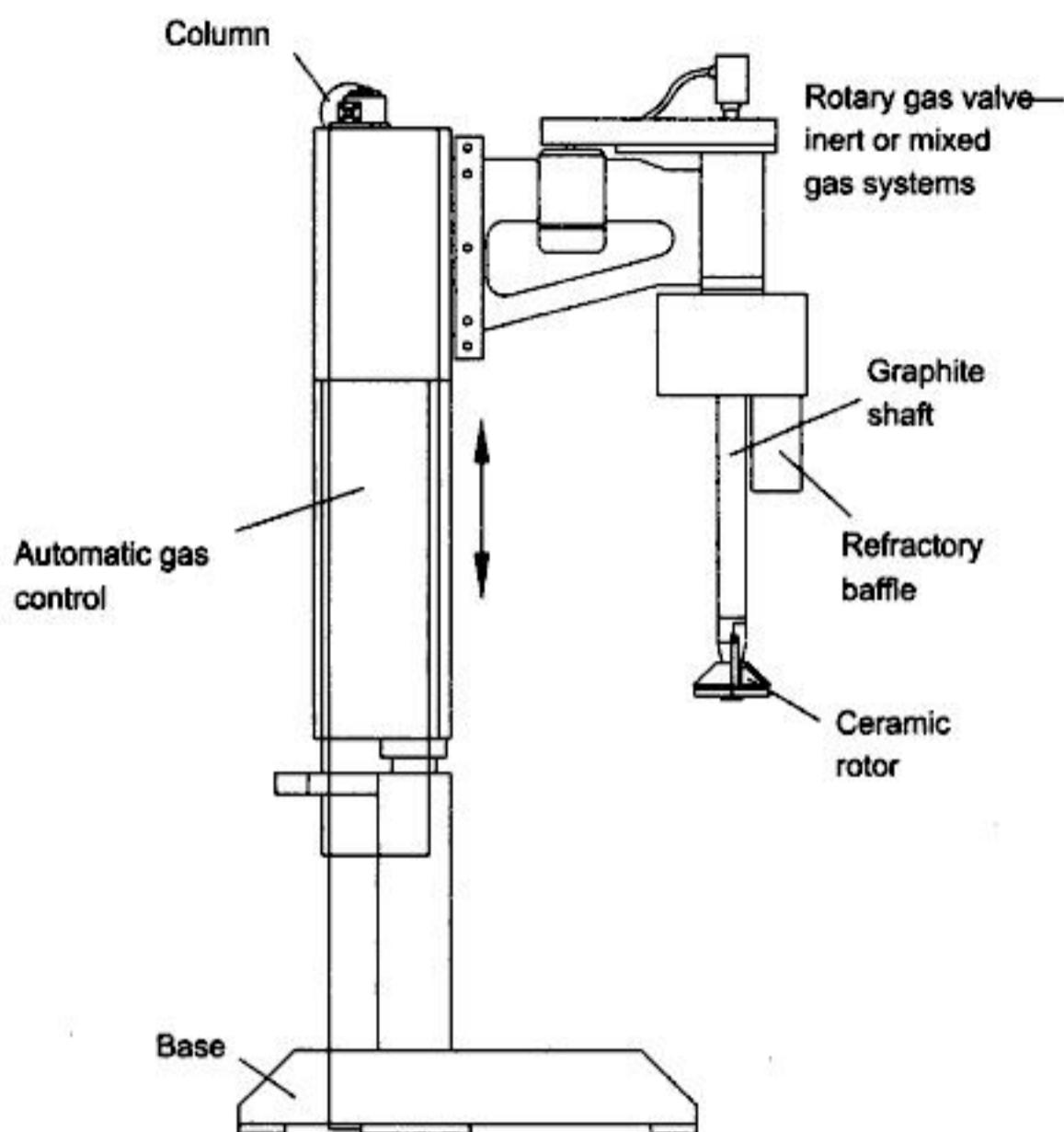


Fig. 5.5 *Rotary degassing unit (Foseco)*

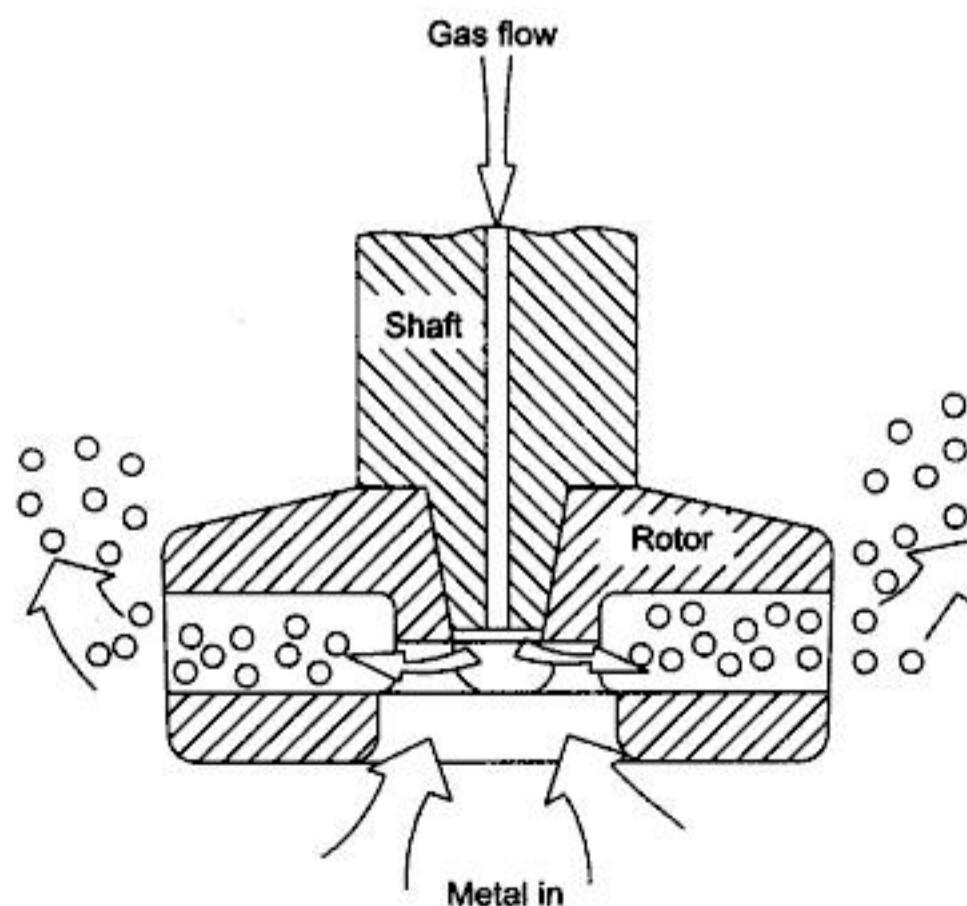


Fig. 5.6 *Close up view of the rotor action of the Foseco Rotary degassing unit*



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For cleaning the sand particles sticking to the casting surface, sand blasting is normally used. The casting is kept in a closed box and a jet of compressed air with a blast of sand grains or steel grit is directed against the casting surface, which thoroughly cleans the casting surface. The typical shot speeds reached are of the order of 80 m/s. The shots used are either chilled cast iron grit or steel grit. Chilled iron is less expensive but is likely to be lost quickly by fragmentation. In this operation, the operator should be properly protected.

Another useful method for cleaning the casting surface is *tumbling*. Here, the castings are kept in a barrel which is completely closed and then slowly rotated on a horizontal axis at 30 to 40 rpm. The barrel is reasonably packed, with enough room for castings to move so that they will be able to remove the sand and unwanted fins and projections. However, one precaution to be taken for tumbling is that the castings should all be rigid with no frail or overhung segments, which may get knocked off during the tumbling operation.

5.3 CASTING DEFECTS

Any irregularity in the moulding process causes defects in castings which may sometimes be tolerated, sometimes eliminated with proper moulding practice or repaired using methods such as welding and metallization. The following are the major defects which are likely to occur in sand castings:

- i) Gas defects
- ii) Shrinkage cavities
- iii) Moulding material defects
- iv) Pouring metal defects
- v) Metallurgical defects

5.3.1 Gas Defects

The defects in this category can be classified into blow holes and open blows, air inclusion and pin hole porosity. All these defects are caused to a great extent by the lower gas-passing tendency of the mould which may be due to lower venting, lower permeability of the mould and/or improper design of the casting. The lower permeability of the mould is, in turn, caused by finer grain size of the sand, higher clay, higher moisture, or by excessive ramming of the moulds.

Blow Holes and Open Blows These are the spherical, flattened or elongated cavities present inside the casting or on the surface as shown in Fig. 5.8. On the surface, they are called *open blows* and inside, they are called *blow holes*. These are caused by the moisture left in the mould and the core. Because of the heat in the molten metal, the moisture is converted into steam, part of which when entrapped in the casting ends up as blow holes or as open blows when it reaches the surface. Apart from the presence of moisture, they occur due to the lower venting and lower permeability of the mould. Thus, in green sand moulds it is very difficult to get rid of the blow holes, unless proper venting is provided.

Air Inclusions The atmospheric and other gases absorbed by the molten metal in the furnace, in the ladle, and during the flow in the mould, when not allowed to escape, would be trapped inside the casting and

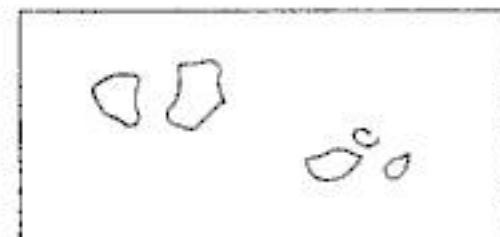


Fig. 5.8 Open blows on the surface of the casting



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As an example, Fig. 5.11(a) shows the possible redesigning of a component. The portions of the hubs projecting above the parting plane at the centre of the casting and the end of one arm are loose pattern parts and are assembled to the main pattern with the help of the dowel pins. But modifying the component as shown in Fig. 5.11(b) would make the parting line straight and thus simplifying the moulding procedure.

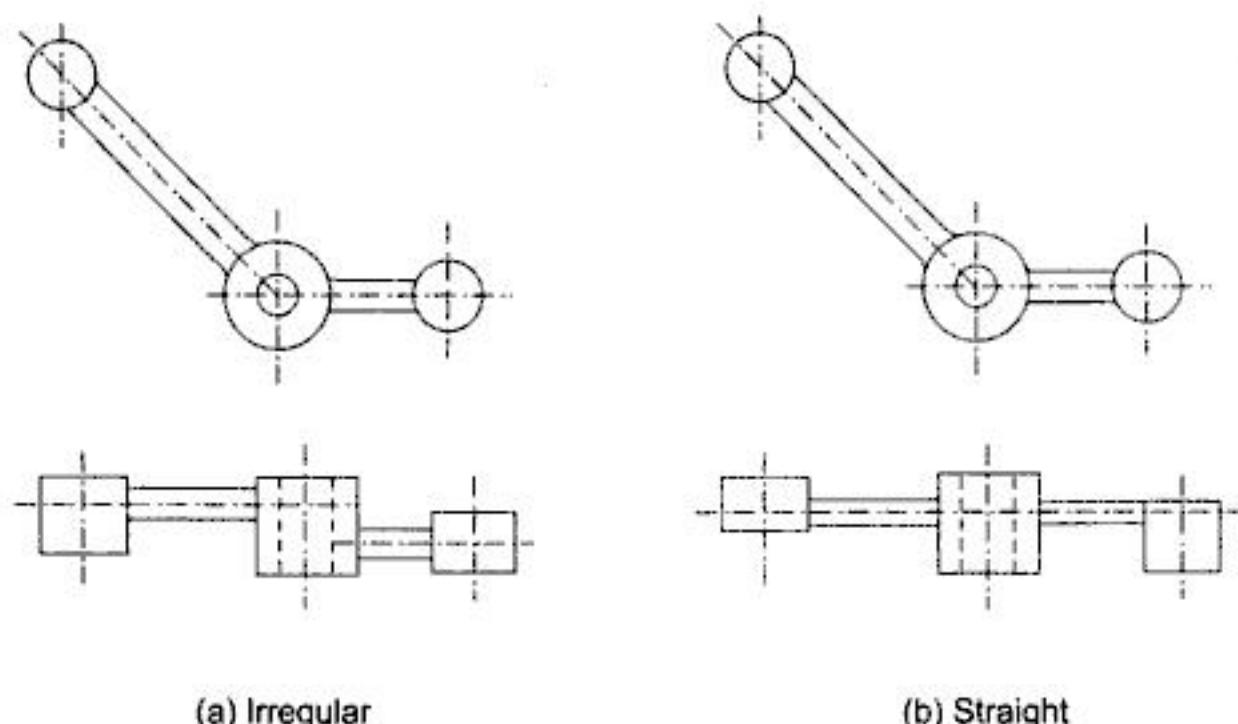


Fig. 5.11 Parting line modification

When an irregular parting results in a deep mould pocket, it may be more economical to redesign the pattern equipment and change over to a mould method with a straight parting involving the use of cores.

Bosses Bosses are frequently used to increase the sectional thickness of the housing and the like in order to provide longer bolt or tap holes or to improve the strength of certain parts of the casting. This may be cast satisfactorily if the axis of the cylindrical boss is parallel to the direction in which the pattern is drawn out of the mould or if the centreline of the boss is in the parting plane. When this is not the case, the boss on the patterns must be loose, and the skilled technique of moulding loose patterns must be employed. The section shown in Fig. 5.12(a) illustrates the positioning of a boss well below a flange whose upper surface is chosen as a parting line. To mould this design, a core is required to permit removal of the pattern from the mould. In producing such a casting as shown, accurate positioning of the core is difficult, and any shifting of the core results in surface irregularities. A somewhat less complicated design in Fig. 5.12(b) extends the boss to the flange, eliminating the undercut and the need for a core.

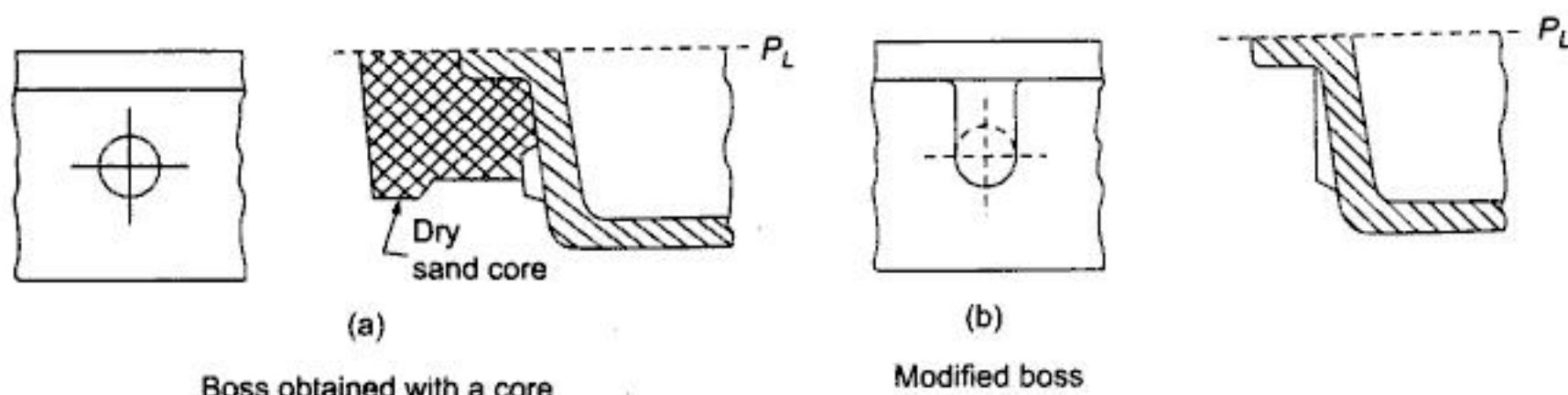


Fig. 5.12 Modification of bosses to reduce dry sand core



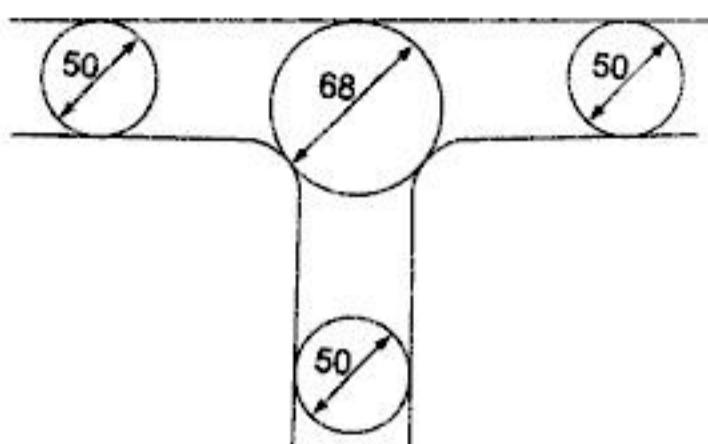
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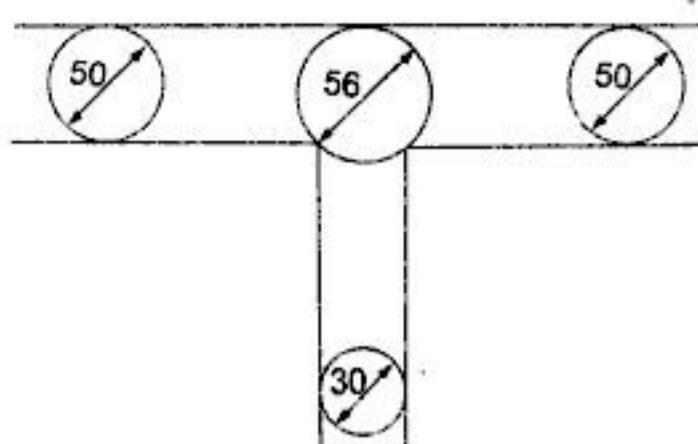
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(a) Wrong

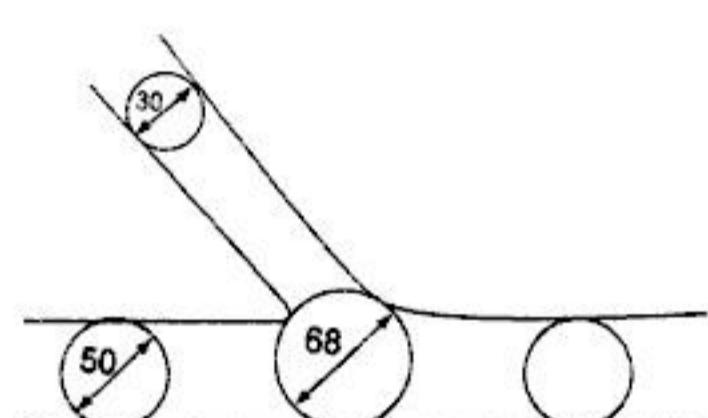


(a) Right

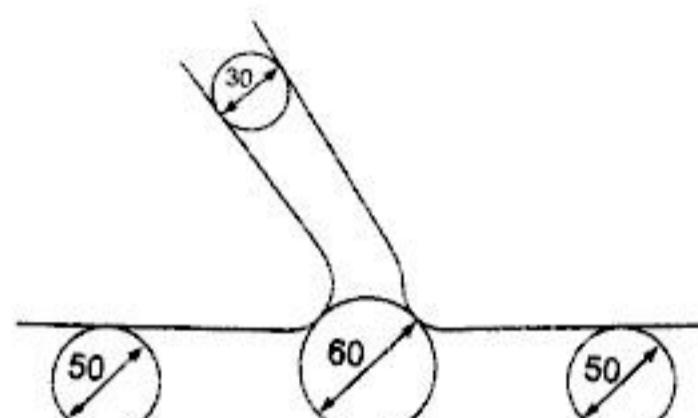
Fig. 5.19 Avoiding concentration of metal at joints

$$\frac{\text{Rib thickness}}{\text{Wall thickness}} = 0.6 \text{ to } 0.8$$

A rib which enters a wall at an angle gives a bigger concentration of metal than one which enters perpendicularly (Fig. 5.20). The former should therefore, be avoided where possible.



(a) Wrong



(b) Preferable

Fig. 5.20 Concentration of metal at angular joint

Extensive investigations have been carried out to reach a common understanding of the problems of junction and fillet design and of the specific effects of design variables on the soundness of the metal in different types of intersections. The castings for these studies, were deliberately produced in such a way that defects were caused to occur at the junctions. Thus the influence of definite junction and corner configuration on the size and number of defects could be observed systematically.

All casting sections were 3×3 inches (76.2 mm). The arms were about 24 inches (609.6 mm) long, with the risers placed at the extreme ends. The risers were utilized as sprues for pouring. The five types of junctions that were considered, are represented by the letters L, T, V, X and Y, by their shapes.

An example of results obtained for L sections are shown in Fig. 5.21. It shows that defects are eliminated by using a 0.5 inch (12.7 mm) fillet and reducing the wall thickness at the corner. No detectable defects were present in the L junction where the radius of the fillet was equal to the wall thickness and a uniform wall was maintained at the corner. In such a design, however, a centreline weakness similar to that in a long uniform wall may be present at the interface, where the two freezing fronts meet. Similar results were obtained for other junctions also.



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6

Special Casting Processes

Objectives

Sand-casting processes described so far are not suitable and economical in many applications. In such situations special casting processes would be more appropriate. After completing the chapter the reader will be able to

- ▶ Understand the shell moulding as a process for higher quality castings with thin surface details
- ▶ Know precision investment casting used for complex shapes
- ▶ Use permanent mould casting for mass production of relatively simple shapes
- ▶ Apply die-casting process for complex parts
- ▶ Understand the advantages of using centrifugal casting process
- ▶ Learn the advantages and applications of various other special casting process.

6.1 SHELL MOULDING

It is a process in which the sand mixed with a thermosetting resin is allowed to come into contact with a heated metallic pattern plate, so that a thin and strong shell of mould is formed around the pattern. Then the shell is removed from the pattern and the cope and drag are removed together and kept in a flask with the necessary back-up material and the molten metal is poured into the mould.

Generally, dry and fine sand (90 to 140 GFN) that is completely free of the clay is used for preparing the shell moulding sand. The grain size to be chosen depends on the surface finish desired on the casting. Too fine a grain size requires large amount of resin, which makes the mould expensive.

The synthetic resins used in shell moulding are essentially thermosetting resins, which get hardened irreversibly by heat. The resins most widely used are phenol formaldehyde resins. Combined with sand, they have very high strength and resistance to heat. The phenolic resins used in shell moulding usually are of the two stage type, that is, the resin has excess phenol and acts like a thermoplastic material. During coating with the sand the resin is combined with a catalyst such as hexa methylene tetramine (hexa) in a proportion of about 14 to 16% so as to develop the thermosetting characteristics. The curing temperature for these would be around 150 °C and the time required would be 50 to 60 s.



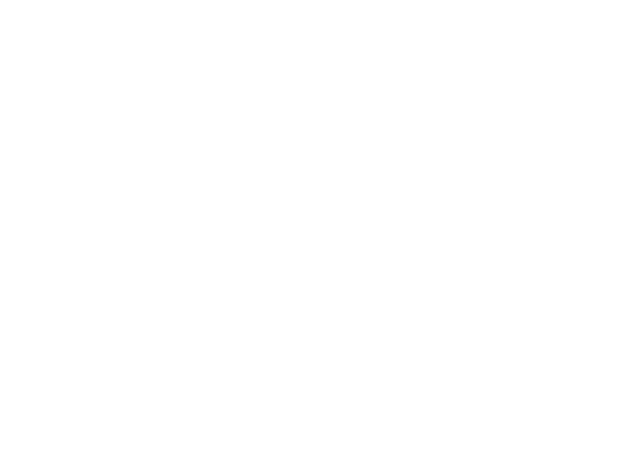
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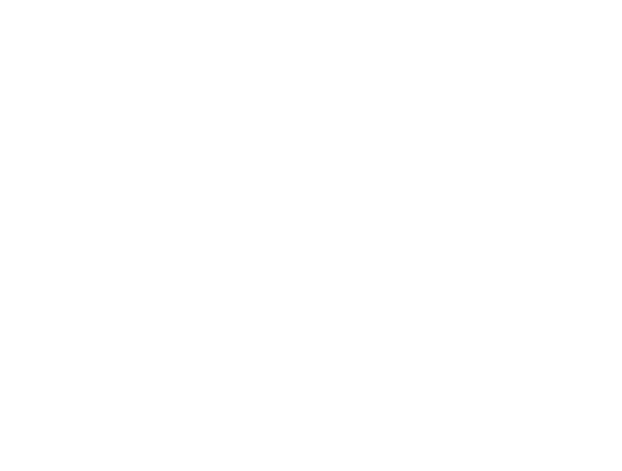
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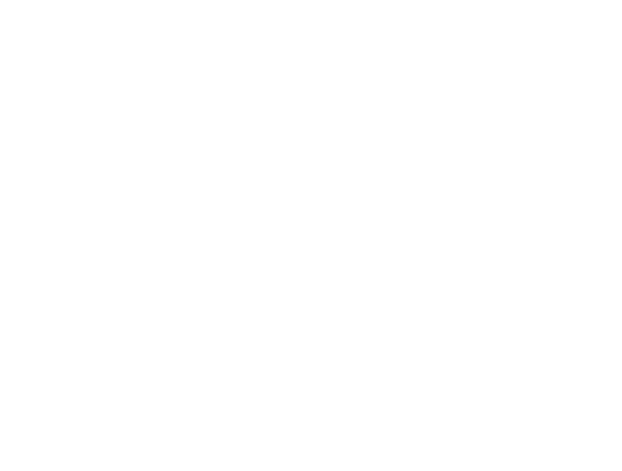
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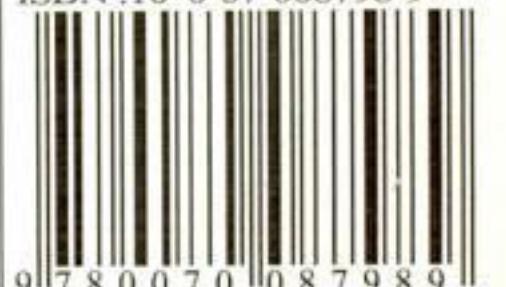
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