To Muhammad Rafique &
Zubaida Rafique
First of all we would like to thank our god almighty ALLAH for giving us the courage, health, energy and patience to complete this task which would have been impossible without his help. Secondly we are very much thankful to our respected teachers for providing us all types of moral, educational and motivational supports. In this regard first we are very much thankful to our project adviser Dr. Javed Iqbal for his cooperative and facilitating behavior and expert advice on all the problems we faced during our project. We are also very much thankful to Dr. Faiz-ul-hassan for helping us in arranging necessary technical facilities for use in our project. We would also like to thank Mr. Furqan Ahmad for helping us in getting micrographs of our samples.

In addition to that we are very much thankful to Mr. Rashid of heat treatment lab, Rana Javed of Inspection and Testing lab. and Mr. Qayyum and Anderayas of Metallography lab for their cooperation and help and Mr. Javed Butt of Libearry for his kind help.

Moreover we would like to thank Mr. Abdul Waheed of Wimza Foundries Lahore for providing us the raw material (gray cast iron) of proper composition in casted form for use as feedstock for machining to make our tensile testing specimens at almost no price. We would also like to thank Mr. M. Rashid of Hafeez Brothers Engineering works for providing us various piston ring samples for use in our experimentation. We would also like to thank Mr. Mudassar Hussain for arranging us a chemical analysis of our samples from Chennab Engineering Works Fasilabad. In this regard we are also very much thankful to Engineers over there.

In the end we are also very much thankful to all the staff of Department of Metallurgical and Materials Engineering UET Lahore for they have been very cooperative and helpful to us throughout.
# Contents

## Chapter-1 Introduction

1. Basic Internal Combustion Engine 9
2. 2.1 Engine Types 9
3. 2.1.2 How an Engine Works 11
4. 2.1.3 Oiling System 13
5. 2.1.4 Engine Cooling 13
6. 2.1.5 Engine Balance 13

## Chapter-2 Literature Survey

2.2 Introduction to Piston Rings 13
2.2.1 Ring Term & Measurements 15
2.2.2 Commonly used Ring Cross Sections 16
2.3 Functions of Piston Rings 17
2.3.1 Gas Seal Function 17
2.3.2 Heat Transfer Function 20
2.3.3 Oil Control Function 21

## 2.4 Piston Ring Design Criteria 22

## 2.5 Sizes and Designs in Piston Rings 22
2.5.1 Piston Ring Sizes 22
2.5.2 Piston Ring Cross-sectional Shapes 22
2.5.3 Working Face Profile 23
2.5.4 Gap Shape 24
2.5.5 Designs 24

## 2.6 Types of Piston Rings 28
2.6.1 Compression Rings 28
2.6.1.1 Top Ring 28
2.6.1.2 Conventional Second Ring 30
2.6.2 Oil Control Ring 31
2.6.2.1 Cross-sectional shapes of Oil Ring Rails 31
2.6.2.2 Appearance of the Oil Ring Spacer 32
2.6.2.3 Two Piece Oil Ring 32

## 2.7 Piston Ring Materials 33
2.7.1 Properties Required
2.7.2 Gray Cast Iron
2.7.3 Modern Materials
   2.7.3.1 Ductile Iron
   2.7.3.2 From Cast Iron to Steel
   2.7.3.3 Comparison of the properties of Cast Iron and Steel
   2.7.3.4 Rings of Steel
   2.7.3.5 More Materials
      2.7.3.5.1 Bronze Materials
      2.7.3.5.2 Teflon
2.8 Piston Ring Heat Treatment
   2.8.1 Heat Treatment of Gray Cast Irons
      2.8.1.1 Annealing
      2.8.1.2 Normalizing
      2.8.1.3 Hardening and Tempering
      2.8.1.4 Austempering
      2.8.1.5 Martempring
      2.8.1.6 Flame Hardening
      2.8.1.7 Induction Hardening
   2.8.2 Heat Treatment of Piston rings
      2.8.2.1 Surface Treatments
         2.8.2.1.1 Top Ring Surface Treatment (IP)
         2.8.2.1.2 Second Ring Surface Treatment
         2.8.2.1.3 Oil Ring & Side Rail Treatment
      2.8.2.1.4 Coefficient of Friction
2.9 General Applications of Piston Rings

Chapter-3 Experimental Work

3.1 Casting
   3.1.1 Rectangular Slabs
   3.1.2 Machining
   3.1.3 Failures
   3.1.4 Recasting in Round Bars
3.2 Chemical Analysis
3.3 Annealing (Stress Relieve)
3.4 Machining
3.5 Samples
3.6 Heat Treatment
   3.6.1 Standard Tensometer Specimen
   3.6.2 Piston Ring Samples
3.7 Tensile Testing on Tensometer
Piston rings are very diversified components of the piston cylinder assembly. They are manufactured in various sizes and ranges and from various materials.

Introduction
Piston rings are very versatile and important components of the engines; they are used in the piston–cylinder assembly in the engine and serve many purposes. Nowadays as the trend is towards more and more powerful as well as environment friendly & economic engines, the job of piston rings is becoming more and more tough.

They are subjected to various types of service abuses including High-pressure, High temperature, Corrosion and erosion from combustion gases, Mechanical wear out, Mechanical forces such as, Bending moments, Flexural stresses, Compression etc. So the requirement for better, stronger, tougher, efficient, economic (cheap) and long life piston rings is increasing.

In this regard many modification are made in manufacturing, surface modification techniques, design and selection of materials to increase the performance and efficiency of piston rings (modern piston rings)

Newer manufacturing techniques are being developed and used in the making of piston rings to make better use of materials properties resulting from specific techniques to increase the performance, reliability and life span of piston rings. For example now days die casting is used to cast individual piston ring in specially matched dies instead of conventional spun casting method which was not only time consuming i-
e time for manufacturing increases due to more number of steps involved e.g. heat treatment, machining, final heat treatment, trimming, final finishing etc. but also poses no control on material properties because material is casted in bulk while manufactured in small thin pieces which can have wide variation in properties from point to point, thus yields poor piston rings. The technique of die casting on the other hand, not only increase the efficiency of piston ring to work in more severe environment but also increase its life by imparting better control on its properties (better compacted structure (high strength), less porosity, better fatigue resistance, close dimensional control, less residual stresses etc.).

Moreover in modern piston ring manufacturing newer surface modification techniques are extensively used which not only decrease the stringent requirements of selection of expensive materials for making whole of piston ring but also decrease the overall cost of piston ring. These allow us to use relatively cheaper materials (e.g. gray cast iron, SG iron etc.) but still maintain the quality of piston rings due to improved properties resulting modification in surface properties. Some of these techniques are gas nitriding, induction hardening, plasma hardening and even flame hardening sometimes; of these gas nitriding is most common. This technique is used on various types of rings which ranges from rings for motor cycles to rings for heavy duty diesel engines to even rings for fast and more powerful turbocharged multicylinder engines. This and other such techniques increase piston ring’s Life, Fatigue resistance, Thermal cyclic resistance, Thermal shock resistance, High temperature resistance and, Resistance against heavy loads.

Some other techniques such as use of conversion coatings are very much common. These conversion coating includes phosphating (blackening), chromizing etc. These conversion coatings are applied through hot dipping, brushing, vapor deposition etc. (Both PVD and CVD) These coating further help in increasing the life of piston rings and also enhances their appearance and outlook.

Newer modified improved designs are also being developed to increase the efficiency performance and life of piston rings. These designs incorporate features such as Improved heat transfer, Improved oil circulation, Improved gas sealing, Resistance against mechanical stresses e.g compression, bending, scratching etc, Smooth and noise free operation with no hang-ups, Saving of material, Ease in manufacturing, Ease in installation and repair and Reduction in cost.

Designs incorporating above features are
- Grooved compression rings (both single and double grooves)
- Chamfered rings instead of straight edge type
- Rings with external inserts
- Rings with locking arrangements etc.

Last but not least newer advanced materials are being developed and used extensively to increase the life and performance of piston rings. Some of the conventionally used materials for piston rings are Gray cast iron, Ductile cast irons, Steels (Both plain carbon and alloyed) etc. While materials used in modern piston rings are gas nitrided steel, titanium coated steel, chromium coated steel, plasma moly steel and ceramics (such as chromium carbide), polymeric materials (PTFE) and composites etc. These advanced materials help increase the piston ring performance way more than anticipated. Newer space age materials such as reinforced composites (PMCs, FRPs),
when used in piston rings, give diversified properties such as Decreased weight, Increased wear resistance, Increased thermal and mechanical shock resistance, No need for lubrication (oiling), Smooth and trouble free operation, Decreased Noise, Decreased cost (cheaper materials) etc.

However these materials have few limitations e.g. (1) these loose their strength considerably in very high temperature environments such as in turbo charged engines (2) They loose their dimensional stability if not properly handled and installed (3) They tend to swell and soften in the presence of fluids e.g. gasoline, water, lubrication oils etc. (in presence of water they loose strength due to moisture absorption)

So they are used but with little caution.

Ceramics were also tried as piston ring materials they give excellent high temperature resistance and dimensional stability with excellent gas seal property, they also provide high compression strength but they suffer from drawbacks such as (1) Brittleness, which is the inherent property of ceramics and due to which they tend to crack very easily. (2) Less mechanical shock resistance. (3) Fragmentation due to repeated mechanical stresses of bending, flexural nature. (4) Difficulty in manufacturing to thin sections due to poor response of ceramics towards manufacturing. (5) Increased cost due to expensive raw materials (Silicon Nitride) and (6) more number of steps involved in manufacturing (compaction, sintering, final trimming etc.)

So their use was restricted as coatings (ceramic coatings) on the steel rings, which serve the purposes such as high wear resistance, high temperature resistance and reduced cost with better efficiency and increased life. However metallic materials such as titanium-coated steel, nitrided steel, chrome moly steel etc. have no such drawbacks and give excellent results. In fact steels have revolutionized the art of making piston rings and most of the modern vehicles such as Honda, Toyota, Mercedes, Ford, Mitsubishi, Ferrari etc. are successfully using these coated steels with a lot of good results with such a smooth operation of engine that it does not seems to be operated at all i.e. very little noise and vibrations are produced during engine operation in the presence of these coated steel piston rings. Further improvements are underway in increasing their efficiency by reinforcing them with fibers (both carbon and glass), Coating them with ceramic coating

That is trend in modern piston ring development is towards the use of hybrid materials also known as metal matrix composites (MMCs) rather then single material, to obtain optimized properties of combination of more then one materials. Moreover in some cases advanced PMCs are used which after certain modification properties, which are much superior then their previous generation
These are top compression, second compression and oil control rings. These are made from high performance titanium coated moly steel.

Literature Survey
2.1 BASIC INTERNAL COMBUSTION ENGINE

Internal combustion gasoline engines run on a mixture of gasoline and air. The ideal mixture is 14.7 parts of air to one part of gasoline (by weight.) Since gas weighs much more than air, we are talking about a whole lot of air and a tiny bit of gas. One part of gas that is completely vaporized into 14.7 parts of air can produce tremendous power when ignited inside an engine.

![A typical Internal Combustion Engine](image)

Fig 2.1: A typical Internal Combustion Engine

Air enters the engine through the air cleaner and proceeds to the throttle plate. Operator controls the amount of air that passes through the throttle plate and into the engine with the gas pedal. It is then distributed through a series of passages called the intake manifold, to each cylinder. At some point after the air cleaner, depending on the engine, fuel is added to the air-stream by either a fuel injection system or, in older vehicles, by the carburetor.

The majority of engines in motor vehicles today are four-stroke, spark-ignition internal combustion engines. Engines like the diesel and rotary engines are however exceptions.

2.1.1 Engine Types

There are several engine types, which are identified by the number of cylinders and the way the cylinders are laid out. Motor vehicles will have from 3 to 12 cylinders, which are arranged in the engine block in several configurations. The most popular of them are shown below in fig 2.2. In-line engines have their cylinders arranged in a row. 3, 4, 5 and 6 cylinder engines commonly use this arrangement. The "V" arrangement uses two banks of cylinders side-by-side and is commonly used in V-6, V-8, V-10 and V-12 configurations. Flat engines use two opposing banks of cylinders and are less common than the other two designs. They are used in Subaru's and Porsches in 4 and 6 cylinder
arrangements as well as in the old Volkswagen beetles with 4 cylinders. Flat engines are also used in some Ferrari's with 12 cylinders.

Each cylinder contains a piston that travels up and down inside the cylinder bore. All the pistons in the engine are connected through individual connecting rods to a common crankshaft.

The crankshaft is located below the cylinders on an in-line engine, at the base of the V on a V-type engine and between the cylinder banks on a flat engine. As the pistons move up and down, they turn the crankshaft just like your legs pump up and down to turn the crank that is connected to the pedals of a bicycle.

A cylinder head is bolted to the top of each bank of cylinders to seal the individual cylinders and contain the combustion process that takes place inside the cylinder. The cylinder head contains at least one intake valve and one exhaust valve for each cylinder. This allows the air-fuel mixture to enter the cylinder and the burned exhaust gas to exit the cylinder.

Most engines have two valves per cylinder, one intake valve and one exhaust valve. Some newer engines are using multiple intake and exhaust valves per cylinder for increased engine power and efficiency.

These engines are sometimes named for the number of valves that they have such as 24 Valve V6 that indicates a V-6 engine with four valves per cylinder. Modern engine designs can use anywhere from 2 to 5 valves per cylinder.

The valves are opened and closed by means of a camshaft. A camshaft is a rotating shaft that has individual lobes for each valve. The lobe is a “bump” on one side of the shaft that pushes against a valve lifter moving it up and down. When the lobe pushes against the lifter, the lifter in turn pushes the valve open. When the lobe rotates away from the lifter, the valve is closed by a spring that is attached to the valve. A very common configuration is to have one camshaft located in the engine block with the lifters connecting to the valves through
a series of linkages. The camshaft must be synchronized with the crankshaft so that it makes one revolution for every two revolutions of the crankshaft. In most engines, this is done by a Timing Chain (similar to a bicycle chain) that connect the camshaft with the crankshaft. Newer engines have the camshaft located in the cylinder head directly over the valves. This design is more efficient but it is more costly to manufacture and requires multiple camshafts on Flat and V-type engines. It also requires much longer timing chains or timing belts, which are prone to wear. Some engines have two camshafts on each head, one for the intake valves and one for the exhaust valves. These engines are called Double Overhead Camshaft (D.O.H.C.) Engines while the other type is called Single Overhead Camshaft (S.O.H.C.) Engines. Engines with the camshaft in the block are called Overhead Valve (O.H.V) Engines.

2.1.2 How an Engine Works

Since the same process occurs in each cylinder, only one cylinder is taken to see how four stroke process works.

The four strokes are Intake, Compression, Power and Exhaust. The piston travels down on the Intake stroke, up on the Compression stroke, down on the Power stroke and up on the Exhaust stroke.

- **Intake**
  As the piston starts down on the Intake stroke, the intake valve opens and the fuel-air mixture is drawn into the cylinder (similar to drawing back the plunger on a hypodermic needle to allow fluid to be drawn into the chamber.) When the piston reaches the bottom of the intake stroke, the intake valve closes, trapping the air-fuel mixture in the cylinder.

- **Compression**
  The piston moves up and compresses the trapped air fuel mixture that was brought in by the intake stroke. The amount that the mixture is compressed is determined by the compression ratio of the engine. The compression ratio on the average engine is in the range of 8:1 to 10:1. This means that when the piston reaches the top of the cylinder, the air-fuel mixture is squeezed to about one tenth of its original volume.
• **Power**
  The spark plug fires, igniting the compressed air-fuel mixture, which produces a powerful expansion of the vapor. The combustion process pushes the piston down the cylinder with great force turning the crankshaft to provide the power to propel the vehicle. Each piston fires at a different time, determined by the engine firing order. By the time the crankshaft completes two revolutions, each cylinder in the engine will have gone through one power stroke.

• **Exhaust**
  With the piston at the bottom of the cylinder, the exhaust valve opens to allow the burned exhaust gas to be expelled to the exhaust system. Since the cylinder contains so much pressure, when the valve opens, the gas is expelled with a violent force (that is why a vehicle without a muffler sounds so loud.) The piston travels up to the top of the cylinder pushing all the exhaust out before closing the exhaust valve in preparation for starting the four-stroke process over again.

*Fig 2.7 Four Stroke cycle*
2.1.3 Oiling System

Oil is the life-blood of the engine. An engine running without oil will last about as long as a human without blood. Oil is pumped under pressure to all the moving parts of the engine by an oil pump. The oil pump is mounted at the bottom of the engine in the oil pan and is connected by a gear to either the crankshaft or the camshaft. This way, when the engine is turning, the oil pump is pumping. There is an oil pressure sensor near the oil pump that monitors pressure and sends this information to a warning light or a gauge on the dashboard. When you turn the ignition key on, but before you start the car, the oil light should light, indicating that there is no oil pressure yet, but also letting you know that the warning system is working. As soon as you start cranking the engine to start it, the light should go out indicating that there is oil pressure.

2.1.4 Engine Cooling

Internal combustion engines must maintain a stable operating temperature, not too hot and not too cold. With the massive amounts of heat that is generated from the combustion process, if the engine did not have a method for cooling itself, it would quickly self-destruct. Major engine parts can warp causing oil and water leaks and the oil will boil and become useless.

While some engines are air-cooled, the vast majority of engines are liquid cooled. The water pump circulates coolant throughout the engine, hitting the hot areas around the cylinders and heads and then sends the hot coolant to the radiator to be cooled off.

2.1.5 Engine Balance

**Flywheel:** A 4-cylinder engine produces a power stroke every half-crankshaft revolution, an 8 cylinder, every quarter revolution. This means that a V8 will be smoother running than a 4. To keep the combustion pulses from generating a vibration, a flywheel is attached to the back of the crankshaft. The flywheel is a disk that is about 12 to 15 inches in diameter. On a standard transmission car, the flywheel is a heavy iron disk that doubles as part of the clutch system. On automatic equipped vehicles, the flywheel is a stamped steel plate that mounts the heavy torque converter. The flywheel uses inertia to smooth out the normal engine pulses.

**Balance Shaft:** Some engines have an inherent rocking motion that produces an annoying vibration while running. To combat this, engineers employ one or more balance shafts. A balance shaft is a heavy shaft that runs through the engine parallel to the crankshaft. This shaft has large weights that, while spinning, offset the rocking motion of the engine by creating an opposite rocking motion of their own.

2.2 INTRODUCTION TO PISTON RINGS

The use of piston rings in engines is very old; they are actually the part of engine, which facilitates the combustion process, and help in the smooth working of the engine. Piston rings are placed in the upper part of the pistons in specially machined grooves. Though
there are various designs of piston rings but they all have some common **features**, which are,

- The part of the piston between the ring grooves and above the top ring that confines and supports the piston ring is known as **Ring Land (A)**
- A narrow groove in the top land used in some pistons to help control heat getting to the top ring is known as **Heat Dam (B)**. It actually fills with carbon in normal operation and limits heat flow to the ring.
- The distance from the pin centerline to the top of the piston is known as **Compression Height (C)**
- The area on the piston between the top of the pin bore and the top of the piston where the ring grooves are machined is called as **Ring Belt (D)**
- The top area of the piston where combustion gas pressure is exerted is called **Piston Head (E)**
- The pin, which connects the rod to the piston with bearing surface, is called **Piston Pin (F)**. It is either press-fit or floating.
- The part of the piston below the ring belt is called **Skirt (G)**.
- The side of the piston carrying the greatest thrustload is called **Major Thrust Face (H)**. Looking at the piston from the front in an engine rotating clockwise, this is the left side.
- The side of the piston opposite the major thrust face is called **Minor Thrust Face (I)**.
- If used, the bushing between the piston pin bore and the pin is known as **Piston Pin Bushing (J)**.

![Fig-2.8 Schematic showing the various parts and terminology of piston rings](image-url)
One or more raised bands of piston material used in some piston designs to reduce scuffing is called **Scuff Band (N)**

The distance between the back of the ring groove and the cylinder wall with the piston centered is known as **Groove Depth (O)**

Piston diameter measured at the back of the groove is called **Groove Root Diameter (P)**. It may vary on the same piston between ring grooves.

Diameter of a given land is called **Land Diameter (Q)**. It can sometimes vary by design from top to bottom.

The difference in diameter between the cylinder bore and the land diameter is called **Land clearance (R)**. "R" is 1/2 the total.

The difference in diameter between the cylinder bore and skirt diameter is called **Skirt Clearance (S)**. "S" is 1/2 the total.

A ring groove cut below the pin bore to carry an oil ring is called **Skirt Groove (T)**

The distance the pin bore is offset from center is known as **Pin Bore Offset (U)**.

**Groove Spacer (V)** It is used on regrooved pistons to return a ring groove to specs or in some performance applications to facilitate the use of narrower ring sets than the grooves were originally cut for.

**Fig-2.9** Schematic showing the various parts and terminology of piston rings

2.2.1 Ring Terms and Measurements

**A. Free gap:** It is the ring end clearance when the ring is uncompressed.

**B. Compressed gap:** Also known as ring gap, it is the end gap measured when the ring is installed.

**C. Radial Wall Thickness:** It is the distance between the inside and outside faces of the ring wall.

**D. Ring Diameter:** Measured with the ring installed.
E. Inside Diameter: Measured with the ring installed.
F. Ring Sides: These are the top and bottom surfaces of the ring.
G. Ring Face: Its is the part of the ring in contact with the cylinder wall.
H. Side Clearance: It is the clearance between the ring groove and the ring.
I. Ring Width: It is the distance between two flat ends of the ring.
J. Torsional Twist: It is the built-in imbalance between the way the upper and lower sides compress that causes a twist in the ring when compressed. It is used to see both the ring in the groove and the ring to the cylinder wall.
K. Back Clearance: It is the distance between the inside diameter of the ring and the bottom of the ring groove with the ring installed.

Fig-2.10 Schematic showing the terms and measurements of piston rings

2.2.2 Commonly Used Ring Cross-Sections

Some of the most commonly used ring cross-sections are
1. Total Seal "Red Head"
2. Dykes
3. Torsional Flat Faced (square cut)
4. Barrel-Faced
5. Total Seal Gapless
6. Taper Faced
7. Reverse Torsional Taper Faced
8. Wiper

Fig-2.11 Schematic showing the terms and measurements of piston rings
2.3 FUNCTIONS OF PISTON RING

The selection of piston rings for an engine is fundamentally related to the engine application. Various vehicles have varying requirements to satisfy which determine the ring materials and designs. Street engines, competitive racing engines, sport engines, and specifically fueled engines such as alcohols and nitrous oxides or even compressed natural gases all may require specific differences in materials and design. Piston rings serve more than one purpose, which are dependent on its specific type of design and conditions of use. However its main functions are,

1-Gas Seal Function.
2-Heat Transfer Function.
3-Oil Control Function.

2.3.1 Gas Seal function

This means that the combustion chamber should be made as **gas-tight** as possible, so that the pressure generated by the quickly burning combustion gases will move the piston in the cylinder causing the crankshaft to turn, making power available. Not only important for the combustion/expansion stroke, gas-tightness is also very important, for the intake, compression and exhaust as well, this general function can be simply called **gas sealing**

In the installed condition (when the gap is closed), the piston ring must form a **circle** such that its periphery (running face) contacts the cylinder wall all the way around. This is a critical requirement. If the ring doesn't seal against the cylinder wall, combustion gases will leak to the outside. It's interesting to note that the ring **does not press** with uniform force all the way around its circumference, from one gap-end to the other.

![Fig 2.12 Schematic showing various types of contact pressure Distribution](image)

**Fig 2.12 Schematic showing various types of contact pressure Distribution**

In fact, this contact pressure can be controlled during ring manufacture to guarantee that the desired contact pressure distribution is achieved in the assembled engine. The figure 2.12 above show how the ring's contact pressure can be different, depending on the particular engine's specific requirements.

The free gap and shape of the ring in its uninstalled condition will determine how much tension is present in the installed ring and which type of pressure distribution is achieved. The ring gap area must be designed to have minimum up and down movement
since excessive dynamic movement would result in **poor** gas sealing characteristics even when the ring has good **roundness**. The ring designer must consider the specific engine application and then design the ring's free shape and free gap in order to achieve proper ring tension and the desired contact pressure distribution in the installed condition.

In addition to requiring excellent roundness, the ring must also be designed such that there is the right **gap** or contact between the piston groove and the piston ring to assure proper gas sealing.

It is important that the piston ring seal tightly against the piston during piston movement or else combustion gases will leak as shown in the figure 2.13. For this reason, the top and bottom surfaces of the piston ring are precision ground to a smooth surface roughness of approximately 1 micrometer. This **flatness** ensures tight seating in the piston groove and good sealing characteristics.

**Fig 2.13** Schematic showing gap between ring and piston groove

If the piston ring in the running engine does not stay seated against the piston groove, a possible **leakage path** for combustion gas is created. When a ring moves upward in the piston groove, a condition known as **ring lift** may be occurring. Rapid up-and-down movement of the ring in the groove is referred to as **fluttering**. Such ring movement is unwanted and contributes to pressure leakage from the combustion chamber. A variety of technologies are employed to control ring position and prevent fluttering during engine operation.

**Fig 2.14** Schematic showing condition of ring left

The above figure 2.14 shows a simplified drawing of a power cylinder. It can be easily seen that the ring has **lifted off** the bottom flank of the piston groove, allowing combustion gas to pass (leak) behind it. There are several ways to prevent this lift. We
will now focus on one such method: adjusting the closed gap dimensions (S1) of the upper and lower compression rings (Top and 2nd rings).

In the figure 2.15 below, the $S1$ dimension refers to the **closed gap** (gap clearance). This is the gap that remains between the ring ends when the ring is closed to its working diameter (cylinder bore diameter).

![Fig 2.15 Schematic representation showing closed gap](image)

- $d_i$: Nominal diameter (mm)
- $R$: Radius ($d_i/2$) (mm)
- $h_i$: Width (mm)
- $a_i$: Thickness (mm)
- $s_i$: Gap clearance (mm)
- $F_t$: Tangential force (N) needed to close free gap clearance to the nominal diameter
- $F_d$: Diametrical force (N) needed to keep the diameter at a position $90^\circ$ from the abutment equal to the nominal diameter when the said force is applied to the said position
- $m$: Free gap clearance (mm)

This closed gap is very small, mere fractions of a millimeter, but it is always there when the ring is closed to its working diameter. Under both high and low temperatures, there is a **temperature difference** between the piston ring and the other cylinder components (cylinder & piston, etc.). Additionally, the **materials** of each component are usually different resulting in different rates of thermal expansion for the cylinder, piston, and piston ring. Taking these factors into consideration, the closed gap must be designed in a way to prevent the gap ends of the closed ring from contacting each other.

Since $S1$ must be a positive number, the ring always has a slight gap opening (usually about 0.3mm) while the engine is operating. Even though this gap is very small, there is still slight gas pressure leakage that could lead to ring flutter. By balancing the $S1$ values of the Top and Second rings (gap balancing), the ring designer can achieve a
balance of pressures, such that the pressure between Top and 2nd rings is never sufficient to lift the Top ring from its seat on the bottom flank of the piston groove during the phase of highest cylinder pressure (combustion/expansion stroke). This gap balancing or adjusting the closed ring gaps (S1) of the compression rings is an accepted method for minimizing top ring flutter and its negative effects on cylinder gas sealing.

2.3.2 Heat Transfer function

The piston ring acts to carry heat away from the hot piston into the cooled cylinder wall/block of the engine. Heat energy flows from the piston groove into the piston ring and then into the cylinder wall, where it eventually will be transferred into the engine coolant. This heat transfer function is very important to maintaining acceptable temperatures and stability in the piston and piston ring, so that sealing ability is not impaired.

![Fig 2.16 Schematic showing Heat transfer function of Piston rings](image)

The piston and top piston ring come into direct contact with hot combustion gases. The figure 2.17 below shows typical temperatures of the various cylinder system components in an operating engine. As can be seen, temperatures range from approx. 184°C to 201°C in the area near the piston rings.

![Fig 2.17 Schematic showing temperature profiles in piston ring cylinder assembly](image)
The heat energy in the piston is absorbed by the rings. The rings then transfer this heat into the cylinder walls and eventually into the engine coolant or into the surrounding air (air-cooled engine). The table shown below provides data on this heat dissipation and transfer phenomenon under different engine operating conditions.

Since the piston rings are in firm contact with both the piston and cylinder wall, they can take heat energy from the piston and transfer this heat into the cylinder. The graph above shows that approx. 70% of the piston's heat is carried away by the piston rings, under both unloaded and loaded engine operation conditions, at 1,500 and 3,000 rpms.

The piston ring designer is very aware of the rings' heat transfer function and is careful to select the right piston ring materials and correct dimensions to ensure adequate cooling effect on the cylinder system components.

2.3.3 Oil Control Function

The piston ring requires some oil for lubrication, however it is desirable to keep this amount to a minimum. The rings act in a scraping manner, keeping excess oil out of the combustion chamber. In this way, oil consumption is held at an acceptable level and harmful emissions are reduced.
2.4 PISTON RING DESIGN CRITERIA

The following are some of the questions that must be addressed before designing a properly functioning ring:

- Does the finished piston ring conform to the cylinder walls of the engine? Even a tiny gap between the ring’s running face and the cylinder wall will provide a leakage path for hot combustion gases and/or engine oil.
- Does the ring press against the cylinder wall with enough force to generate the necessary unit pressure (contact pressure)?
- Can the chosen ring material withstand extremely hot combustion gases?
- Is the ring material also resistant to corrosive attack by the hot exhaust gases?
- Can the ring withstand a high-speed operation without losing performance?
- Does the ring avoid improper movement (i.e., not 'pounding out' its groove in the piston)?
- Is the ring scuff-resistant, even at the upper point of the piston and cylinder, where lubrication is very poor and friction force is very high?
- Does the ring show adequate life characteristics, i.e., even when the engine is being operated at 2,000 to 3,000 rpm, the ring must last many thousands of operating hours (= years!)?
- Can the ring survive the bitterest cold in very cold climates and also the highest temperatures in very hot climates?
- Does the ring perform its function well without generating too much friction?

The rings are checked and tested against these criteria again and again before they are approved for installation in a production engine.

2.5 SIZES AND DESIGNS IN PISTON RINGS

Engines come in a variety of shapes and sizes depending on the application. There are applications requiring enormous engine output as well as applications needing engines that can be hand carried. A piston ring designer must take the specific nature of the particular application into account when deciding upon ring characteristics.

2.5.1 Piston Ring Sizes

Piston rings are manufactured in all sizes from finger ring size to larger than 1 meter in diameter. Used for lawn & garden equipment and marine engines respectively, these sizes represent the extreme ends of the piston ring size range. The greatest numbers of rings are produced for automobile and light truck engines with diameter sizes ranging from 70mm to 100mm in diameter (Fig 2.20)

2.5.2 Piston Ring Cross-sectional Shapes

The cross-sectional shape of the ring will vary and is determined by such factors as
- Which ring it is (i.e., top, second, oil)?
- Which functions it has to perform?
- What material and/or surface coating is called for? and
• By the particular engine application.

![Various sizes of piston rings](image)

**Fig 2.20** Various sizes of piston rings

- Keystone ring
- Napier ring (undercut step)
- Bevelled edge - oil control ring
- Coil spring loaded bevelled-edge oil control ring

**Fig 2.21** Piston ring Cross-sectional shapes

### 2.5.3 Working face profile

The working or running face of the upper and lower compression rings will show one of the following configurations:

![Working face profiles](image)

- Straight - faced
- Barrel - faced
- Taper - faced

**Fig 2.22** Outer Periphery shapes
2.5.4 Gap Shape

The ring gap creates a possible gas leakage path. In certain applications, special gap shapes are designed to minimize the gap clearance in order to decrease unwanted gas leakage.

Fig 2.23 schematic showing various gap shapes

2.5.5 Designs

A large variety of type, style, and materials are available for use in industrial gas, diesel, and steam engines. The following Ring types are commonly manufactured for today's natural gas engines.

Fig 2.24 Simple compression ring
Up to 32" diameter

A one-piece sealing ring with an overlapping joint designed to prevent blow-by in either new or worn cylinders. The alloy-sealing member is permanently bonded along its entire length and will neither break nor come off. The angular design of the sealing member and its recess holds both ends of the ring together in perfect alignment as pressure is applied. The greater the pressure, the tighter the sealing tongue is locked in its recess, forming an unbroken circle without any protrusion, which could cause scoring or port clipping. This ring is highly recommended for most types of internal combustion engines and hydraulic equipment. This ring is shown in figure 2.24 above.

Fig 2.25 Super Moly compression ring

Up to 22" diameter

The Super Moly Compression Ring is the latest advancement in hard surfacing of piston rings. It is available in oxyacetylene plasma applied molybdenum alloys. The Super Moly Ring seats quickly, and its oil-retaining quality (due to high porosity) provides the best ring available for top groove application in turbo-charged engines and severe operating conditions. A Moly-filled ring offers faster breaking time and may be run in either cast iron or chrome cylinders. This is shown in fig 2.25 above.

Fig 2.26 Plain compression ring
Up to 32" diameter
This is a standard, plain concentric, quick-seating piston ring of one-piece construction for maximum strength. Butt cut, angle cut and step cut joints are available. These are also available as chrome plated. Shown in fig 2.26 above.

Fig 2.27 Taper Face compression ring

Up to 22" diameter
There is a slight taper on the outside face, which provides line contact of high unit pressure with the cylinder wall for quicker seating and faster break-in. This is available in butt cut unless otherwise specified. This is also available in chrome plated condition. This is shown in fig 2.27 above.

Fig 2.28 Bronze band compression ring
**Up to 22'' diameter**

This is standard one-piece compression ring with one or two bronze bands, depending on the ring dimensions. The bronze band is permanently bonded and fused to the body of the ring; this construction does not weaken the ring and the bronze bands will not work loose.

This is available in butt cut unless otherwise specified. Shown in fig 2.28 above

![Plain Compression Ring](image)

**Fig 2.29 Chrome Plated compression ring**

**Up to 22'' diameter**

This is chrome plated. This chrome plating offers increased hardness to ring face, reduces abrasive wear and adds corrosion resistance to ring face. Chrome Plated rings are available with either a fine finish or groove face finish. Chrome Plated rings should not be used in chrome plated cylinders. Shown in fig 2.29.

![Heavy Duty Oil Ring with Coil Expander](image)

**Fig 2.30 Heavy Duty Oil ring with Coil Expander**
Up to 22" diameter

This Heavy Duty Oil Control Ring is the most efficient conformable design for use in piston grooves provided with oil drainage return through the groove root diameter. The narrow undercut oil scrapers will retain their calculated unit wall load even with normal expected wear in long service, providing economical oil consumption throughout the life span of ring set.

Fig 2.31 Super Oil Scraper Ring with Coil Extender

Up to 22" diameter

The Super Oil Scraper is a highly efficient conformable oil control ring to be used where piston grooves are not provided with oil drainage in their root diameter. The two narrow undercut oil scraping edges efficiently peel oil from the cylinder wall, yet maintain a calculated pressure against the cylinder even as the ring wears in long service. Oil relief ports are machined on lower scraper edge to allow for oil drainage. (Fig 2.31)

2.6 TYPES OF PISTON RINGS

There are two basic types of piston rings

a) Compression Rings
b) Oil Ring

Further compression rings have two types;

- Top Ring
- Second Ring

2.6.1 Compression Rings

2.6.1.1 Top Ring

The top ring or fire ring is known as the compression ring and is expected to seal against pressure losses from the combustion process. The compression ring is also expected to maintain a high build-up of pressure as the piston arrives at the top.

Fig 2.32 Types of piston rings
of the stroke when at a predetermined location the combustible mixture is ignited building up pressure to force the piston downward. The ability of the piston ring to maintain this pressure is contingent on a couple of important items. The ring gap is critical to this event and obviously burning gases do flow through this gap. The ring gap is also critical to the function of the top ring as it is related to its stability. In addition to this the fire ring is a barrier and transfers a large portion of the heat through its contact with the cylinder wall.

The top ring is shown in fig 2.33 below for a 86mm diameter cylinder bore. The ring's axial width (height) is 1.2mm and its radial thickness is 3.1mm. The ring in the photo is shown in the so-called free state, that is, what the ring looks like before installation into the engine. The free gap (open portion of the ring) is about 9mm.

When the ring is installed (on the piston) in the engine, it is squeezed closed to its effective diameter of 86mm. Since the ring wants to expand back to its free state, this built-in springiness makes the ring fit tightly against the cylinder wall. The force needed to close the ring to 86mm can be measured and is usually called ring tangential tension. Tangential tension is an important ring characteristic and is always considered carefully during the design phase of piston ring manufacturing.

Looking at the outside shape of the ring; peripheral working face (or 'running face') of the ring can be seen. This running face stays in contact with the cylinder wall, usually cushioned on a thin layer of oil. This surface slides on the cylinder wall and some resistance, called sliding friction, is generated.

Fig 2.33 Top compression ring

Here we show a profile of the ring's running face magnified 1000 times. Under magnification, the surface appears to be composed of minute convex spherical surfaces. This surface shape plays an important role in forming an oil film during high-speed operation. A hard film of CrN (nitrided chromium) is formed on the running face by an ion plating (known as IP) process. Other surface treatments for the ring's running face include nitriding and hard chrome plating.

Fig 2.34 Running face of top compression ring
2.6.1.2 Conventional Second Ring or Secondary Compression Ring

The second ring is probably the most misunderstood ring application of all the rings used on a piston. With a conventional piston ring the ring design is similar to the top ring. It also has a ring gap, which allows hot gases to further penetrate down the cylinder wall into the crankcase oil. This is known as blow-by and has deleterious effects on the engine. Blow-by getting into the oil contaminates the oil with carbon particles from the combustion process, raises the acid level, heats up the oil and speeds up the oxidation process. This effectively begins the process of slowly diminishing the lubrication ability of the oil and allows the carbon particles to wear out all the parts, which it is expected to lubricate. The second ring also serves as an oil scraper ring to help minimize the oil above the second ring and as such compliments both the compression ring and the oil ring.

For a 86mm cylinder bore second ring has an axial width (height) of 1.2mm and a radial thickness of 2.9mm. Looking at the appearance of the second ring's running face, it can be seen that it serves to complement the top ring in its gas sealing function, but it also provides oil control. Fig 2.35 shows the free gap and running face of the second ring.

![Fig 2.35 Free gap and running face of Second compression ring](image)

When squeezed closed to its 86mm working diameter, the ring's tension will hold it tightly against the cylinder wall, providing a sealing function. At the same time, the ring's undercut bottom side produces a running face profile that acts to scrape oil downward. A magnified measurement trace (fig 2.36) shows the ring's running face in profile. This face is not straight vertical, but is tapered. This ring shows a taper face angle of approximately 1° 30'. This taper-face profile provides good gas sealing action, efficient oil scraping action, and allows for a fast running-in period (break-in phase).

![Fig 2.36 Magnified measurement trace of running face of second ring](image)
2.6.2 Oil Control Rings

Oil control rings are designed along with the piston to effectively permit lubrication of the rings, pistons, wrist pins and cylinder walls without oil migrating into the combustion process. Oil Rings also assist the thermal control of the piston by directing oil into the inside of the piston to help cool the piston dome. Several types of oil rings are available as may be required including the popular three-piece ring consisting of an expander and two rails. The expander provides the tension for the rails and is sold in more than one tension depending on the application. When installing an expander, the expander joint is to be 90 degrees to the wrist pin and the rails should be 1" apart centered on each side of the wrist pin end.

Engine lubricating oil performs an essential protective function in the engine by allowing parts to slide and by preventing them from making direct metal-to-metal contact (reducing friction), which causes wear, and in the worst case, total engine failure. Engine oil reduces operating friction, making the engine more efficient; while also serving to cool critical engine components and trapping harmful dirt particles.

![Fig 2.37 Appearance of the oil ring](image)

Fig 2.37 shows how oil ring is assembled. This 3-piece oil ring is installed into the piston groove and functions as an assembly to generate the required performance. The oil ring assembly above has a diameter of 86mm, an axial width of 2.0mm and a radial thickness of 2.5mm.

2.6.2.1 Cross Sectional Shapes of the Oil Ring Rails

The thin, upper and lower plate-shaped rings are referred to as rails. Each rail is about 0.4mm wide. Each oil ring assembly requires two rails: an upper rail and a lower rail. The periphery of each rail makes contact with the cylinder walls and slides. A hard film of CrN (nitrided chromium) has been applied to the running face by an ion plating process.
Other surface treatments for the rails' running face include nitriding and hard chrome plating.

2.6.2.2 Appearance of the Oil Ring Spacer

The wave design seen in the picture below Fig (2.38) allows the spacer to act as a spring. The spring action of the spacer presses the rails against the cylinder wall until the correct tension and unit wall pressure are achieved.

![Enlarged View of the Oil Ring Spacer](image)

**Fig 2.38 Oil ring spacer**
As mentioned above, the two rails and the spacer form an oil ring set or assembly. This is why it is referred to as a **three-piece ring**. Even after assembly, the total axial width is a surprisingly narrow 2.0mm!

2.6.2.3 Two Piece Oil Ring

![STD Narrow Type](image)

**Fig 2.39 Two Piece oil ring**
The oil ring illustrated above is a two-piece assembly that is used most often for diesel engine applications. We refer to this ring as a Diesel Vent-M (DVM) oil ring assembly. This oil ring assembly consists of a M-shaped steel rail and a cylindrical coil spring. The DVM is characterized by its lightweight, high conformability and its ability to accurately control oil and reduce oil consumption.

2.7 PISTON RING MATERIAL

2.7.1 Properties Required

Piston ring materials must possess the following characteristics in order for the ring to perform its functions under the most severe operating conditions. Moreover, these characteristics must be retained over the engine's entire operating life; not just when it is first brought into service!

**Toughness:** The material must withstand high forces and at the same time be able to deflect (move), in order to ensure conformability without breaking or fatiguing over time.

**Elasticity:** The material must be able to act like a spring when the ring is closed to its working diameter. This 'springiness' generates the tension that allows the ring to maintain its designed contact pressure on the cylinder wall.

**Corrosion Resistance:** The material must be resistant to chemical and physical changes caused by corrosive combustion gases and high temperatures.

**Surface Treatment Characteristics:** The chosen surface treatment must be compatible with the base material and show optimal wear, friction, and scuff-proof behaviors as established by the design requirements.

**Light weight:** Reduced reciprocating mass will limit energy losses during high-speed operation. Lighter weight also means lower inertial forces acting on the rings during operation.

**Long Service Life:** The selected piston ring material must be able to retain the above performance characteristics over the service life of the engine even under high temperature conditions.

2.7.2 Gray Cast Iron

Grey cast iron is a perfectly adequate ring material for most passenger car applications as long as the rings are of sufficient size to handle the loads. But the change to thinner low-tension rings combined with efforts to squeeze more power out of smaller displacement engines has increased the operating loads on the rings, especially the top compression ring that receives the brunt of the punishment. Uncoated grey cast iron is compatible with cast iron cylinder walls and won’t gall or scuff, but it’s also brittle. Bend a ring that’s made out of grey cast iron too far and it will snap. The material has little "give" because of its microstructure. When you examine the grain structure of grey cast iron under a microscope, it has sharp rectangular grains that easily fracture if the metal is shock loaded or bent too far (a good reason for always using a ring expander when installing rings on a piston).

With narrow low tension rings (1.5 mm or 5/64 inch) grey cast iron rings can break if the engine is subjected to heavy or continuous detonation. The hammer-like
blows produced by the colliding flame fronts shock loads the rings and can break them resulting in a

- Loss of compression
- Cylinder damage and
- Oil consumption problems.

Though this danger can be minimized to a large extent in engines with computerized engine controls by using a knock sensor to retard spark timing, there’s no guarantee it can protect the rings under all circumstances.

Various alloys of grey cast iron are available, including "intermediate" alloys that are somewhat harder (28 to 38 HRC) and stronger. Rings made out of these alloys are used uncoated for the second compression ring in many engine applications as well as the top ring in two cycle engines. Chrome or moly coated intermediate grey cast iron rings are also used for top compression rings.

2.7.3 Modern Materials

2.7.3.1 Ductile Iron

The above-mentioned problems bring us to ductile iron rings. Ductile iron has been used for years for heavy-duty truck gas and diesel rings because ductile iron is roughly twice as strong as grey cast iron. Ductile iron is also called nodular iron because its microstructure contains rounded or nodular shaped grains. These increase strength and allow the metal to bend without breaking. Consequently, ductile iron compression rings can take a lot more pounding than grey cast iron rings without breaking. In fact, you can bend a ductile iron ring like a pretzel and it won’t snap. That’s why the domestic vehicle manufacturers have been using ductile iron compression rings in many turbocharged and high output engine applications in recent years. Ductile iron has also been a popular choice for racers because of its ability to hold up in a high rpm, high stress racing environment.

But ductile iron has two drawbacks. One is that it is more expensive than grey cast iron. The basic material costs more and it is more expensive to machine. The other is that ductile iron is not as compatible with cast iron cylinder walls as grey cast iron. It tends to scuff and gall unless it is faced with chrome or moly. So, it is said that although ductile iron rings are definitely superior to grey cast iron, they aren’t always necessary.

"Ductile iron rings are used in all turbocharged engines and most of the engines developed since the early 1980s with 1.5 mm top compression rings to reduce the danger of ring breakage. But the higher cost of ductile iron does not always translate to better. There is absolutely no advantage to using high strength ductile iron in an engine that doesn’t require it. It’s like putting 100 octane fuel into a car with a 7.5 to 1 compression ratio.

"The one advantage ductile iron does offer is that it has a lot of bending strength and is very resistant to breaking. It is also has greater hardness, but this does not necessarily mean it is more wear resistant. Most of the abrasives that cause premature ring wear will wear a ductile iron ring just as fast as an ordinary grey cast iron ring. It’s the moly or chrome coating on the ductile ring that helps retard the wear rate."
2.7.3.2 From Cast Irons to Steel

Cast iron has been and still is a key piston ring material. However, engine design has continued to evolve. To meet the ever-increasing performance demands of modern engines, piston ring materials have been changing as well. In many applications, steel rings have replaced iron rings because:

1) Steel has high strength and great toughness that allows the ring to be made thinner and lighter.
2) Steel has greater resistance to heat which means less deformation and ring tension relaxation over time.
3) Steel is an excellent base material for a variety of surface treatments that reduce friction and prolong ring service life.

2.7.3.3 Comparison of the Properties of Cast Iron and Steel.

**Strength:** High strength is desirable because it allows a thinner piston ring to withstand the stresses of ring operation and movement in the groove. Even the highest grades of cast iron cannot match the strength of steel.

**Thermal Fatigue Resistance:** The ring material must be able to maintain its required tension for its entire service life. Higher resistance is desirable because the material becomes weaker over time when exposed to prolonged high temperature. Steel offers more superior thermal fatigue resistance than cast iron.

**Modulus of Elasticity:** A higher modulus value means that the material must be deflected less to produce the equivalent spring effect. Steel has higher elasticity (200 ~ 215 MPa) compared to cast iron (157 ~ 167 MPa), which allows for thinner and lighter ring design.

**Corrosion Resistance and Surface Modification Characteristics:** Not only must the base material be corrosion resistant; it must also be adaptable to variety of surface treatment processes. Since there are now a large number of surface treatment options for the designer, highly adaptable base materials are desired.

2.7.3.4 Rings of Steel

The next step up from ductile iron is steel. As we said earlier, ductile iron is roughly twice as strong as grey cast iron, and steel is roughly twice as strong as ductile iron. So steel rings can really take a pounding without failing.

Here’s how the three alloys compare:

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Hardness</th>
<th>Tensile Strength</th>
<th>Fatigue strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey Cast iron</td>
<td>22-23 HRC</td>
<td>45,000 psi</td>
<td>30,500 psi</td>
</tr>
<tr>
<td>Ductile iron</td>
<td>38-40 HRC</td>
<td>180,000 psi</td>
<td>87,300 psi</td>
</tr>
<tr>
<td>Steel (SAE9254)</td>
<td>44-53 HRC</td>
<td>240,000 psi</td>
<td>138,600 psi</td>
</tr>
</tbody>
</table>

As can be seen, steel is harder, has a higher tensile strength and higher fatigue strength than either ductile or grey cast iron. How this actually translates into ring
strength and wear resistance depends on the size and shape of the rings themselves. But generally speaking, steel rings provide:

- Better breakage resistance.
- Improved heat resistance.
- Better mechanical stress resistance.
- Reduced ring side wear.
- Reduced groove side wear.
- Longer service life.

It is further said by experts that steel rings can **solve** a lot of problems. They’re stronger, harder, seal better and resist breakage and wear under load. They are ideal for any application that involves higher combustion temperatures, higher compression loads and tougher emission standards. "The SAE 9254 high alloy steel that is used in rings also lowers engine oil consumption. The lighter ring provides a more effective seal against the bottom of the ring groove. The smaller cross section, permitted by the greater strength, also improves the ability of the ring to conform to less-than-perfect cylinder bores. And compared to ductile or cast iron, the inherent strength of steel creates less chance of ring breakage. Steel also provides longer service life and a reduction in ring side wear and ring groove pound out."

Steel has become the ring material of choice among many racers today. "Of the last 29 NASCAR races of the ’92 season, 16 winners were running our Speed Pro steel top compression rings."

Like ductile iron, steel is not compatible with cast iron cylinder walls, so it must be **coated** with either chrome or moly or gas nitrided which will be described later. The rings are made from **preformed steel wire**, much in the same fashion as the steel rails for oil rings. The wire comes from the steel supplier coiled like a Slinky, which is then cut to form the rings. The rings are slightly distorted (like a lock washer), however, from being coiled, so after they’re heat treated and shaped the sides must be ground flat. The steel ring is then chrome plated or face coated with plasma moly that is inserted into a recess in the face of the ring.

Most of the steel rings currently in production have a width of 1.2 mm (0.047 in.). Some are as small as 1.0 mm. Such rings are found in many late model Japanese engines. The 1.2 mm rings are about as thick as two oil ring rails stacked together, so there’s not a lot of space to machine a groove for a moly facing. That’s why the rings are usually chrome plated or gas nitrided.

The amount of **machining** that’s required to finish a steel ring is far less than that which is required to finish grey cast iron or ductile iron rings, so steel rings are actually less expensive to manufacture—at least in large batches. In smaller batches, however, getting steel supplier to provide the special wire that’s required can get costly—which is why the domestic ring manufacturers are taking a "wait-and-see" attitude towards expanding their coverage of steel rings for applications that do not use steel as original equipment.

It is further said by experts that there’s really no advantage of going to steel in a full size ring. "Steel lends itself best to the narrow low tension ring applications because it’s too stiff for the wider rings".
Steel rings are usually **barrel faced**, having contoured outside diameters, which gives the ring a center contact with the cylinder wall. The extremely narrow 1.0 mm rings usually have a tapered face.

Most of the ring manufacturers have said steel is unquestionably the **ring material of the future**, especially for the top compression ring. Like ductile iron, it is very resistant to breakage. But it’s also less expensive to manufacture.

Most of the new engines that are being introduced are going to steel. Ford’s 4.6L modular V8, which was introduced several years ago and initially used ductile iron top compression rings have been refitted with steel rings for 1993.

Though steel rings are starting to be used in newer domestic engines, most of the domestic ring manufacturers are currently using ductile iron for applications that require a premium ring material. According to most ring manufacturers, steel and ductile iron rings can be considered virtually interchangeable as far as rebuilding most passenger car gasoline engines is concerned. So if a steel replacement ring is not available for a certain application that uses steel as original equipment, you can substitute ductile iron.

"Many of these newer engines are designed around the ductile or steel rings. If you don’t use the right type of ring, your customer is going to have ring problems 20,000 miles or so down the road."

2.7.3.5 More materials

2.7.3.5.1 Bronze Materials

These are used primarily in a poor lubrication service and in an application where corrosive liquids or gases might cause Cast Iron to fail.

1. **Grade C96300 Bronze**
   A high-quality Leaded Tin Bronze, which has been found to be more suitable in general applications.

2. **Grade C93700 Bronze**
   A high-quality Leaded Bronze with certain percentages of Lead and Bronze, frequently used in a poor lubrication service.

Other grades of Bronze are also useable but the above two are the more popular grades.

3. **Grade 'C' MICARTA® Grade 'C' BAKELITE**
   A medium weave, cotton fabric base laminate. Properties equal requirements of NEMA C.E. Molybdenum-disulfide lubricant has benn added to the Phenolic Resin to further reduce friction. These Rings operate with very little lubrication and have a maximum continuous operating temperature of 250° F.

4. **Grade ARC-2 SPAULDITE® “HIGH TEMP BAKELITE”**
   These materials have anti-friction and anti-wear characteristics built in through the addition of Molybdenum-disulfide to the resin. These superior materials allow for top performance over a wide range of operating conditions, from low temperatures to a continuous 375° to 425° F. temperature, with little lubrication, these materials are used in Piston Rings, Rider Rings, Compressor Valve Plates, and Rotary Valves.

2.7.3.5.2 Teflon

DuPont's Polytetrafluoroethylene is used to achieve a quality of performance, which exceeds all other materials in non-lubricated applications. This is due to its' phenomenal native lubricity and frictionless properties. Chemically inert and uniquely wear resistant,
Teflon is extremely tough and is available in three additive blends all especially developed to operate in lubricated or non-lubricated service. Teflon Glass filled, Teflon Glass Moly filled and Teflon Carbon filled each possess notable wear resistance impervious to corrosive gases, moisture, and temperature extremes.

![Fig 2.40 Standard PTFE Piston Rings](image)

2.8 PISTON RING HEAT TREATMENT

2.8.1 Heat Treatment of Gray Cast Irons

Gray Irons are a group of cast irons that form flake graphite during solidification, in contrast to the spheroidal graphite morphology of ductile irons. The flake graphite in gray iron is dispersed in a matrix with a microstructure that is determined by composition and heat treatment. The usual microstructure of gray iron is a matrix of pearlite with the graphite flakes dispersed throughout. In terms of composition, gray irons usually contain 2.5 to 4% C, 1 to 3% Si, and additions of manganese, depending on the desired microstructure (as low as 0.1% Mn in ferritic gray irons and as high as 1.2% in pearlitic). Other alloying elements include nickel, copper, molybdenum, and chromium.

The heat treatment of gray irons can considerably alter the matrix microstructure with little or no effect on the size and shape of the graphite achieved during casting. The matrix microstructures resulting from heat treatment can vary from ferrite-pearlite to tempered martensite. However, even though gray iron can be hardened by quenching from elevated temperatures, heat treatment is not ordinarily used commercially to increase the overall strength of gray iron castings because the strength of the as-cast metal can be increased at less cost by reducing the silicon and total carbon contents or by adding alloying elements. The most common heat treatments of gray iron are annealing and stress relieving.

Chemical composition is another important parameter influencing the heat treatment of gray cast irons. Silicon, for example, decreases carbon solubility, increases the diffusion rate of carbon in austenite, and usually accelerates the various reactions during heat treating. Silicon also raises the austenitizing temperature significantly and reduces the combined carbon content (cementite volume). Manganese, in contrast, lowers the austenitizing temperature and increases hardenability. It also increases carbon
solubility, slows carbon diffusion in austenite, and increases the combined carbon content. In addition, manganese alloys and stabilizes pearlitic carbide and thus increases the pearlite content.

2.8.1.1 Annealing

The heat treatment most frequently applied to gray iron, with the possible exception of stress relieving, is annealing. The annealing of gray iron consists of heating the iron to a temperature high enough to soften it and/or to minimize or eliminate massive eutectic carbides, thereby improving its machinability. This heat treatment reduces mechanical properties substantially. It reduces the grade level approximately to the next lower grade: for example, the properties of a class 40 gray iron will be diminished to those of a class 30 gray iron. The degree of reduction of properties depends on the annealing temperature, the time at temperature, and the alloy composition of the iron.

Gray iron is commonly subjected to one of three annealing treatments, each of which involves heating to a different temperature range. These treatments are ferritizing annealing, medium (or full) annealing, and graphitizing annealing.

**Ferritizing Annealing.** For an unalloyed or low-alloy cast iron of normal composition, when the only result desired is the conversion of pearlitic carbide to ferrite and graphite for improved machinability, it is generally unnecessary to heat the casting to a temperature above the transformation range. Up to approximately 595°C (1100°F), the effect of short times at temperature on the structure of gray iron is insignificant. For most gray irons, a ferritizing annealing temperature between 700 and 760°C (1300 and 1400°F) is recommended.

**Medium (full) annealing.** It is usually performed at temperatures between 790 and 900°C (1450 and 1650°F). This treatment is used when a ferritizing anneal would be ineffective because of the high alloy content of a particular iron. It is recommended, however, to test the efficacy of temperatures below 760°C (1400°F) before a higher annealing temperature is adopted as part of a standard procedure.

Holding times comparable to those used in ferritizing annealing are usually employed. When the high temperatures of medium annealing are used, however, the casting must be cooled slowly through the transformation range, from about 790 to 675°C (1450 to 1250°F).

**Graphitizing Annealing.** If the microstructure of gray iron contains massive carbide particles, higher annealing temperatures are necessary. Graphitizing annealing may simply serve to convert massive carbide to pearlite and graphite, although in some applications it may be desired to carry out a ferritizing annealing treatment to provide maximum machinability.

The production of free carbide that must later be removed by annealing is, except with pipe and permanent mold castings, almost always an accident resulting from inadequate inoculation or the presence of excess carbide formers, which inhibit normal graphitization; thus, the annealing process is not considered part of the normal production cycle.

To break down massive carbide with reasonable speed, temperatures of at least 870°C (1600°F) are required. With each additional 55°C (100°F) increment in holding
temperature, the rate of carbide decomposition doubles. Consequently, it is general practice to employ holding temperatures of 900 to 955°C (1650 to 1750°F).

### 2.8.1.2 Normalizing

Gray iron is normalized by being heated to a temperature above the transformation range, held at this temperature for a period of about 1 hour per inch of maximum section thickness, and cooled in still air to room temperature. Normalizing may be used to enhance mechanical properties, such as hardness and tensile strength, or to restore as-cast properties that have been modified by another heating process, such as graphitizing or the preheating and postheating associated with repair welding.

The temperature range for normalizing gray iron is approximately 885 to 925°C (1625 to 1700°F). Austenitizing temperature has a marked effect on microstructure and on mechanical properties such as hardness and tensile strength.

The tensile strength and hardness of a normalized gray iron casting depend on the following parameters:

- Combined carbon content
- Pearlite spacing (distance between cementite plates)
- Graphite morphology.

The graphite morphology does not change to any significant extent during normalization, and its effect on hardness and tensile strength is omitted in this discussion on normalizing.

Combined carbon content is determined by the normalizing (austenitizing) temperature and the chemical composition of the casting. Higher normalizing temperatures increase the carbon solubility in austenite (that is, the cementite volume in the resultant pearlite). A higher cementite volume, in turn, increases both the hardness and the tensile strength. The alloy composition of a gray iron casting also influences carbon solubility in austenite. Some elements increase carbon solubility, some decrease it, and others have no effect on it. The carbon content of the matrix is determined by the combined effects of the alloying elements.

The other parameter affecting hardness and tensile strength in a normalized gray iron casting is the pearlite spacing. Pearlite spacing is determined by the cooling rate of the casting after austenitization and the alloy composition. Fast cooling results in small pearlite spacing, higher hardness, and higher tensile strength. Too high a cooling rate may cause partial or full martensitic transformation. The addition of alloying elements may change hardness and tensile strength significantly.

### 2.8.1.3 Hardening and Tempering

Gray irons are hardened and tempered to improve their mechanical properties, particularly strength and wear resistance. After being hardened and tempered, these irons usually exhibit wear resistance approximately **five** times greater than that of pearlitic gray irons.

**Furnace or salt bath** hardening can be applied to a wider variety of gray irons than can either flame or induction hardening. In flame and induction hardening, a relatively large content of combined carbon is required because of the extremely short
period available for the solution of carbon in austenite. In furnace or salt bath hardening, however, a casting can be held at a temperature above the transformation range for as long as is necessary; even an iron initially containing no combined carbon can be hardened.

**Unalloyed gray iron** of low combined carbon content must be austenitized for a longer time to saturate austenite with carbon. With increased time, more carbon is dissolved in austenite and hardness after quenching is increased. Because of its higher silicon content, an unalloyed gray iron with a combined carbon content of 0.60% exhibits higher hardenability than a carbon steel with the same carbon content. However, because of the effect of silicon in reducing the solubility of carbon in austenite, unalloyed irons with higher silicon contents necessarily require higher austenitizing temperatures to attain the same hardness.

Manganese increases hardenability; approximately 1.50% Mn was found to be sufficient for through hardening a 38 mm section in oil or for through hardening a 64 mm section in water.

Manganese, nickel, copper, and molybdenum are the recognized elements for increasing the hardenability of gray iron. Although chromium, by itself, does not influence the hardenability of gray iron, its contribution to carbide stabilization is important, particularly in flame hardening.

**Austenitizing.** In hardening gray iron, the casting is heated to a temperature high enough to promote the formation of austenite, held at that temperature until the desired amount of carbon has been dissolved, and then quenched at a suitable rate.

The temperature to which a casting must be heated is determined by the transformation range of the particular gray iron of which it is made. The transformation range can extend more than 55°C above the $A_t$ (transformation-start) temperature. A formula for determining the approximate $A_1$, transformation temperature of unalloyed gray iron is:

$$A_1 \ (°C) = 730 + 28.0 \ (% \ Si) - 25.0 \ (% \ Mn)$$

Chromium raises the transformation range of gray iron. In high-nickel, high-silicon irons, for example, each percent of chromium raises the transformation range by about 10 to 15°C. Nickel, on the other hand, lowers the critical range. In a gray iron containing from 4 to 5% Ni, the upper limit of the transformation range is about 710°C.

Castings should be treated through the lower temperature range slowly, in order to avoid cracking. Above a range of 595 to 650°C, which is above the stress-relieving range, heating may be as rapid as desired. In fact, time may be saved by heating the casting slowly to about 650°C in one furnace and then transferring it to a second furnace and bringing it rapidly up to the austenitizing temperature.

**Quenching.** Molten salt and oil are the quenching media used most frequently for gray iron. Water is not generally a satisfactory quenching medium for furnace-heated gray iron; it extracts heat so rapidly that distortion and cracking are likely in all parts except small ones of simple design. Recently developed water-soluble polymer quenches can provide the convenience of water quenching, along with lower cooling rates, which can minimize thermal shock.

The least severe quenching medium is air. Unalloyed or low-alloy gray iron castings usually cannot be air quenched because the cooling rate is not sufficiently high
to form martensite. However, for irons of high alloy content, **forced-air quenching** is frequently the most desirable cooling method.

**Tempering.** After quenching, castings are usually tempered at temperatures well below the transformation range for about 1h per inch of thickest section. As the quenched iron is tempered, its hardness decreases, whereas it usually gains in strength and toughness.

### 2.8.1.4 Austempering

In austempering, the microstructural end product of the gray iron matrix formed below the pearlite range but above the martensite range is an **acicular** or **bainitic ferrite**, plus varying amounts of austenite depending on the transformation temperature. The iron is quenched from a temperature above the transformation range in a hot quenching bath and is maintained in the bath at constant temperature until the austempering transformation is complete.

In all hot quenching processes, the temperatures to which castings must be heated for austenitizing and the required holding times at temperature prior to quenching in the hot bath correspond to the temperatures and times used in conventional hardening, that is, temperatures between 840 and 900°C (1550 and 1650°F). The holding time depends on the size and chemical composition of the casting.

Gray iron is usually quenched in salt, oil, or lead baths at 230 to 425°C for austempering. When high hardness and wear resistance are the ultimate aim of this treatment, the temperature of the quench bath is usually held between 230 and 290°C. The effect of iron composition on the holding time may be considerable. **Alloy additions**, such as nickel, chromium, and molybdenum, increase the time required for transformation.

### 2.8.1.5 Martempering

Martempering is used to produce **martensite** without developing the high stresses that usually accompany its formation. It is similar to conventional hardening except that distortion is minimized. Nevertheless, the characteristic brittleness of the martensite remains in a gray iron casting after martempering, and martempered castings are almost always tempered. The casting is quenched from above the transformation range in a salt, oil, or lead bath: held in the bath at a temperature slightly above the range at which martensite forms (200 to 260°C or 400 to 500°F. for unalloyed irons) only until the casting has reached the bath temperature; and then cooled to room temperature.

If a wholly martensitic structure is desired, the casting must be held in the hot quench bath only long enough to permit it to reach the temperature of the bath. Thus, the **size and shape** of the casting dictate the duration of martempering.

### 2.8.1.6 Flame Hardening

Flame hardening is the method of **surface hardening** most commonly applied to gray iron. After flame hardening, a gray iron casting consists of a hard, wear-resistant outer
layer of martensite and a core of softer gray iron, which during treatment does not reach the At transformation temperature.

Both unalloyed and alloyed gray irons can be successfully flame hardened. However, some compositions yield much better results than do others. One of the most important aspects of composition is the combined carbon content, which should be in the range of 0.50 to 0.70%, although irons with as little as 0.40% combined carbon can be flame hardened. In general, flame hardening is not recommended for irons that contain more than 0.80% combined carbon because such irons (mottled or white irons) may crack in surface hardening.

**Effects of Alloying Elements.** In general, alloyed gray irons can be flame hardened with greater ease than can unalloyed irons, partly because alloyed gray irons have increased hardenability. Final hardness also may be increased by alloying additions. The maximum hardness obtainable by flame hardening an unalloyed gray iron containing approximately 3% total carbon, 1.7% Si, and 0.60 to 0.80% Mn ranges from 400 to 500 HB. This is because the Brinell hardness value for gray iron is an average of the hardness of the matrix and that of the relatively soft graphite flakes. Actually, the matrix hardness on which wear resistance depends approximates 600 HB. With the addition of 2.5% Ni and 0.5% Cr, an average surface hardness of 550 HB can be obtained. The same result has been achieved using 1.0 to 1.5% Ni and 0.25% Mo.

**Stress Relieving.** Whenever practicable or economically feasible, flame-hardened castings should be stress relieved at 150 to 200°C.

### 2.8.1.7 Induction Hardening

Gray iron castings can be surface hardened by the induction method when the number of castings to be processed is large enough to warrant the relatively high equipment cost and the need for special induction coils.

Considerable variation in the hardness of the cast irons may be expected because of a variation in the combined carbon content. A minimum combined carbon content of 0.40 to 0.50% C is recommended for cast iron to be hardened by induction, with the short heating cycles that are characteristic of this process. Heating castings with lower combined carbon content to high hardening temperatures for relatively long periods of time may dissolve some free graphite, but such a procedure is likely to coarsen the grain.

### 2.8.2 Heat Treatment of Piston Rings

Vehicle and machine operators share a common wish: to have the best fuel economy and to have the longest possible oil change intervals. The periphery (running face) of a piston ring requires a material that reduces contact friction as much as possible and still allows the ring to perform its sealing function against the cylinder wall. Even though the ring's running face is usually gliding on a very thin layer of oil, the friction force can be large. Minimizing such friction losses is therefore another challenge that faces today's piston ring designer. This can be effectively achieved through heat treatment.

Although **hard chrome plating** and **nitriding** are well-proven coatings for a piston ring's running face surface, current trends in engine design are driving the development of new piston ring materials and face coatings.
2.8.2.1 Surface Treatments

A number of different surface treatments are applied, depending upon the engine's particular application and the design concept of the power cylinder system. It must be emphasized that the inter-related power system components, the cylinder, the piston, and the piston rings, must all be optimized for the specific application and bring similar qualities of high performance and long service life. Recently developed face coatings have been proven under the most severe engine operating conditions.

2.8.2.1.1 Top Ring Surface Treatment (IP)

This is a CrN film applied to the ring by an ion plating process. This process produces outstanding hardness on the running face: Hv values of 1500 or more compared to Hv 400~500 for the ring base material. The ion planting (IP) layer is a type of PVD film that offers the following characteristics:

1. Low coefficient of friction
2. High hardness
3. High adhesion to base metal
4. Excellent scuff resistance

2.8.2.1.2 Second Ring Surface Treatment (Nitriding)

This family of processes produces a hard surface layer on the base material. In these processes, nitrogen atoms penetrate and diffuse into the base metal, significantly increasing the surface hardness.

Looking at the layer hardness value as a function of distance from the ring surface, it can be seen in the graph below that the hardness at the surface is over Hv 1,100.

![Graph showing hardness value as function of distance from ring surface](image)

**Fig 2.41** Graph showing hardness value as function of distance from ring surface
2.8.2.1.3 Oil Ring and Side Rail (Segment Surface Treatment)

Depending on the application, *IP film, nitriding, and chrome plating* are all surface treatment options.

2.8.2.1.4 Coefficient of Friction

It is desirable to make this number as low as practically possible since it plays a large role in engine wear and efficiency. From the table below it can be seen that *IP* coating has the lowest coefficient of friction of any of the available surface coatings.
2.9 GENERAL APPLICATIONS OF PISTON RINGS

Steel compression piston rings have been used for 30 years or more in many heavy-duty truck applications because steel is the best material for withstanding the extreme loads experienced inside high compression turbocharged and supercharged diesel engines. But steel rings didn’t make the transition to automotive applications until the auto makers started downsizing ring dimensions to reduce friction and weight. The Japanese were the first, switching to steel top compression rings about ten years ago. Ford and General Motors have followed suit, using steel in a couple of applications (the Ford 1.9L and Buick 3800 V6).

A large variety of type, style, and materials of piston rings are now available for use in industrial gas, diesel, and steam engines.

Do you drive a car every day? Have you traveled by ship or used products that were transported by ship? Do we rely on trucks to supply local stores or drive on roads that were built by construction equipment such as bulldozers? Do we eat food that was grown and harvested using farm tractors and combines?

All of these machines, lawn mowers, passenger cars, transport lorries, construction equipment, farm implements, cargo and passenger ships, are powered by internal combustion engines, usually of the reciprocating (piston) type, using gasoline or diesel oil as fuel.

An important working part in these engines is something called a piston ring. It's a precision-made component that helps the engine harness the energy contained in the fuel and converts it into useful power. In fact, piston rings are absolutely essential to an engine’s efficiency and durability, as well as to meeting all necessary emission regulations. So piston rings are used in all above-mentioned machinery for their efficient and perfect work and their importance is increasing day by day as we are shifting towards more and more high-tech machinery.
Tensometer shown is used extensively for tensile testing of metallic specimens. It yields data about tensile and related properties of metals.
3.1 CASTING

For obtaining the standard tensile specimens to determine the mechanical properties of gray cast iron, first the bulk material of exactly the same chemical composition as that of piston rings was casted.

3.1.1 Rectangular Slabs

First material was casted in rectangular shapes. Two slabs of 12cm x 6 cm x 2 cm were casted using standard sand casting technique. The scrap of gray cast iron was melted in graphite refractory crucible in a gas fired pit furnace. The slabs were casted in drag portion of the mold and given some time for solidification (5-6 minutes). After solidification they were shaken out, fettled and cleaned for any unwanted fins and fissures.

![Rectangular casted slabs of gray cast iron](image)

**Fig 3.1** Rectangular casted slabs of gray cast iron

3.1.2 Machining

After casting rectangular slabs were subjected to machining operation. For this purpose first they were cut into rectangular bars by the help of power hack saw then they were gripped in the jaws of universal chuck of the lathe machine and machined with the help of high speed steel tool.
3.1.3 Failures

After little machining the bars fractured in to two pieces in a **brittle manner** and stopped further machining. The bars become unusable for further work as well because their shape was distorted and dimensions were changed. This happened due to brittleness in the as cast structure of cast iron. One of the bars was successfully machined after a modified, long, tedious and hard process of machining but others remain as such and all required samples could not be made.

3.1.4 Recasting in Round Bars

To avoid the above-mentioned problems the material of piston rings was recasted in round bars instead of rectangular shapes. Two bars of following dimensions were casted using same procedure as that used for the casting of rectangular slabs.

![Fig 3.2 Schematic showing the round casted bar](image)

Length = 12 inches
Diameter = 1 inch

3.2 CHEMICAL ANALYSIS

After recasting in round bars one sample was cut from round bars and subjected to wet chemical analysis

**Procedure**

This analysis is carried out in standard *Strohlein apparatus*. In this method both **carbon** and **sulfur** in a ferrous material is determined very quickly in one operation. For this carbon is oxidized at a high temperature in a stream of dry and pure oxygen to yield carbon dioxide. The carbon dioxide is absorbed in soda lime or KOH solution. The decrease in volume of the gas after absorption is read directly on a scale as percentage of carbon, after making the due corrections in the volume for the change in temperature and pressure. The sulfur present in the material is also oxidized to SO$_2$, which is absorbed in H$_2$O$_2$ and titrated with a standard NaOH solution. Other elements were detected by little modification in procedure [10].

**Results of Chemical Analysis**

The results of the wet chemical analysis are **Si 2.03%, C 3.362%, S 0.1%, Mn 0.6%, P 0.2%**.
3.3 ANNEALING (Stress Relieve)

Keeping in mind the rectangular slab failure and the fact of presence of internal solidification stresses in the casting, the samples for machining were subjected to stress relieve annealing to remove the stresses in as cast structure and to facilitate machining. For this purpose samples were put in an electric resistance heat treatment furnace at 600°C for 50 minutes. Time and temperature are selected such that grain growth doesn’t occur but graphitization of carbide is accomplished. This treatment removed the as cast structure and the associated stresses with that and made possible the easy machining of brittle gray cast iron.

3.4 MACHINING

After stress relieve annealing the round bar samples were machined on center lathe machine. For this purpose first bars were subjected to facing operation, which involves the reduction in length by movement of the tool from center of the part to its surface. This operation establishes the dimensions of the part along its length by removing outer edge irregularities at both ends (i.e. left and right). Followed by that parts were smoothened for their outer surface by turning operation. This process involves continuous diameter reduction across the length of part when tool moves from right to left on lathe machine, this dia reduction improves the surface finish and dimensional accuracy of the part and removes any surface or sub-surface discontinuities. After this operation step turning was carried out in which part was successively reduced in diameter from certain designated positions to ultimately form the actual shape.

3.5 SAMPLES

Samples obtained after machining were of following shape

Fig 3.3 Schematic showing Standard Tensometer tensile specimen
3.6 HEAT TREATMENT

In heat treatment, first austenitizing was carried out, for **austenitization** electric resistance heating furnace was used which was heated upto 850°C, it took about 3-4 hours for furnace to reach at 850°C from ambient temperature.

3.6.1 Standard Tensometer Specimens

1. **Quenched in Water**
   The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched in water maintained at ambient temperature in a container. During quenching water was kept shaken to get uniform quenching results.

2. **Quenched in Oil**
   The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched in oil maintained at ambient temperature in a container. During quenching oil was kept shaken to get uniform quenching results.

3. **Quenched in Brine (10% NaCl soln.)**
   The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched in brine maintained at ambient temperature in a container. During quenching brine was kept shaken to get uniform quenching results.

4. **Quenched in Ice Water**
   The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched in ice water maintained in a container. During quenching water was kept shaken to get uniform quenching results.

5. **Martempered**
   The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched to 200°C in another furnace maintained at that temperature, held there for 10 minutes and then cooled in air.
6. Austempered
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 10 minutes and then was quenched to 300-400°C in another furnace maintained at that temperature held there for 25 minutes and then quenched in water.

3.6.2 Piston Rings Samples

1. Quenched in Water
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched in water maintained at ambient temperature in a container. During quenching water was kept shaken to get uniform quenching results.

2. Quenched in Oil
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched in oil maintained at ambient temperature in a container. During quenching oil was kept shaken to get uniform quenching results.

3. Quenched in Brine (10% NaCl soln.)
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched in brine maintained at ambient temperature for in a container. During quenching brine was kept shaken to get uniform quenching results.

4. Quenched in Ice Water
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched in ice water maintained in a container. During quenching water was kept shaken to get uniform quenching results.

5. Martempered
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched to 200°C in another furnace maintained at that temperature, held there for 1 minute and then cooled in air.

6. Austempered
The specimen was placed in the furnace, heated to the austenitizing temperature i-e 850°C held there for 1 minute and then was quenched to 300-400°C in another furnace maintained at that temperature, held there for 25 minutes and then quenched in water.

3.7 TENSILE TESTING ON TENSOMETER

After heat treatment standard tensometer specimens were tensile tested on Housenfield Tensometer. For this purpose first selection of load beam, was carried out by calculations.

Suppose
\[
\text{UTS of Gray cast iron (O)} = 295 \text{ MPa} \\
\text{Initial Area (A)} = \frac{\pi D^2}{4} = 3.14(6.12 \times 10^{-3})^2 = 0.00002940 \text{ m}^2
\]
Now as
\[
O = \frac{P}{A} \Rightarrow P = O \times A
\]
\[
P = (295 \times 10^6)(0.00002940)
\]
\[
P = 8637 \text{ N}
\]
\[
P = 8.637 \text{ KN}
\]
So, 10 KN Beam can be used satisfactorily

**Procedure**

For carrying out tensile test, specimen is clamped in the grips of the tensometer. Suitable beam (10 KN) is selected and fitted with machine. Magnification is noted. Initial diameter of the specimen is measured. Graph paper is wrapped over the recording drum and position of the mercury in the scale is brought at zero.

After these arrangements slowly load is applied manually by rotating lever arm with this, rise in mercury level is also checked and points are marked on graph paper by manually operated cursor at frequent intervals. Procedure is carried out until specimen fractures. After this graph paper from drum is taken off and from load vs Extension curve fracture load is measured. Similarly maximum load, load at Yield point are also measured Final dia of the specimen after fracture is also measured. Readings obtained are plotted in terms of stress vs strain curve [7]

**Fig 3.5** Figures showing various steps involved in the tensile testing of metallic specimen on tensometer
3.8 HARDNESS TESTING

Hardness testing was carried out on Rockwell Hardness tester for standard tensile testing specimens.

3.8.1 Rockwell Hardness Testing

For Rockwell Hardness test first suitable scale was selected keeping in mind the type of material. In our case it was C scale because material tested was gray cast iron.

Procedure

For carrying test first specimen surface is cleaned and polished, using emery papers. Then this polished specimen is placed on anvil of machine with polished surface facing indenter. The anvil is raised and specimen is touched to the indenter. Needle on dial gauge indicating minor load is brought to small point (indicated) by raising the anvil; this will show that minor load has been applied. After this major load is applied by releasing lever mechanism, about 30-40 sec time is given for complete application of load. Then major load is removed and reading is directly taken from scale with minor load still being applied. After taking reading major load is also removed and specimen is taken out from machine [7].

3.9 METALLOGRAPHY

For metallography following steps were taken [5],

Sampling
Small specimens were cut from each ring specimen. The selected samples were so carefully cut that we obtained smooth surface of the specimens.

Mounting
The selected specimen for the metallography were so small that they could not be handled easily during polishing so these samples were mounted to facilitate intermediate and final polishing. The bakelite molding powder was used for the mounting purpose. For mounting, the specimen and the correct amount of bakelite were placed in cylinder of the mounting press. The temperature was gradually raised to 150ºC and a molding pressure of about 4000 psi was applied simultaneously. The bakelite set and cured when that temperature was reached, after that specimen mount was ejected from the molding die. Similarly all the specimens were mounted.

Intermediate Polishing
After mounting, the samples were polished on a series of emery papers, containing successively finer abrasives separately. After intermediate polishing the next step was of fine polishing.

Fine Polishing
The final polishing to a flat scratch free surface was obtained by the use of a wet rotating wheel covered with special cloth that was charged with carefully sized abrasive particles (diamond paste was used as an abrasive). Each sample was fine polished using this method.
Etching
After the final polishing of each sample etching was carried out to make visible many structural characteristics of the mounted samples that was accomplished by the use of reagent (etchent) i-e nital (1-5ml HNO₃ + 100ml C₂H₅OH)

Microscopy
In this each of the etched samples was observed separately by using the metallurgical microscope, having an attached camera above the eyepiece (projection microscope) so the metallographic structures were recorded by photographic method. Different features of the heat-treated samples were observed using different magnifications and focusing arrangements. The microstructures were observed for type, amount and nature of phases present and their photographs were taken. Metallography was carried out at 100X and 400X magnifications.
Gray cast iron shows brittle flat fractures when tensile tested on Tensometer. It showed very low tensile strength and very little elongations.

Results
TENSILE TESTING
Following results were obtained after tensile testing of all samples on Tensometer

4.1.1 Untreated

Observations
Original length of specimen ($L_o$) = 50.24 mm
Diameter = 6.08 mm
Area = 29.018624 mm$^2$

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain x10$^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.0625</td>
<td>0.00625</td>
<td>35.0884</td>
<td>126.2626</td>
</tr>
<tr>
<td>2.125</td>
<td>0.0125</td>
<td>71.768</td>
<td>252.5252</td>
</tr>
<tr>
<td>3.1875</td>
<td>0.01875</td>
<td>107.6524</td>
<td>378.7878</td>
</tr>
<tr>
<td>4.25</td>
<td>0.025</td>
<td>143.365</td>
<td>505.0505</td>
</tr>
<tr>
<td>5.3125</td>
<td>0.03125</td>
<td>179.420</td>
<td>631.313</td>
</tr>
<tr>
<td>6.375</td>
<td>0.037</td>
<td>215.30</td>
<td>757.5758</td>
</tr>
<tr>
<td>7.4375</td>
<td>0.04375</td>
<td>251.18</td>
<td>883.8384</td>
</tr>
<tr>
<td>8.5 (Fracture load)</td>
<td>0.05(Final extension)</td>
<td>287.073</td>
<td>1010.10101</td>
</tr>
</tbody>
</table>

Final length of specimen ($L_f$) = 51mm
Elongation = $\frac{L_f - L_o}{L_o} \times 100 = 1.5127\%$

4.1.2 Quenched in water

Observations
Original length of specimen ($L_o$) = 52.5 mm
Diameter = 6.12 mm
Area = \( \frac{\pi D^2}{4} = 0.00002940 \) m\(^2\) = 29.401704 mm\(^2\)

Final length of specimen \( L_f \) = 52.8 mm
Elongation = \( \frac{L_f - L_o}{L_o} \times 100 = 0.5714\% \)

### 4.1.3 Quenched in oil

**Observations**

Original length of specimen \( L_o \) = 50.23 mm
Diameter = 6.08 mm
Area = 29.018624 mm\(^2\)

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain ( \times 10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.07875</td>
<td>0.006875</td>
<td>37.174</td>
<td>136.870</td>
</tr>
<tr>
<td>2.1575</td>
<td>0.01375</td>
<td>74.348</td>
<td>273.741</td>
</tr>
<tr>
<td>3.23625</td>
<td>0.020625</td>
<td>111.523</td>
<td>410.611</td>
</tr>
<tr>
<td>4.315</td>
<td>0.0275</td>
<td>148.70</td>
<td>547.482</td>
</tr>
<tr>
<td>5.39375</td>
<td>0.034375</td>
<td>185.87</td>
<td>684.352</td>
</tr>
<tr>
<td>6.4725</td>
<td>0.04125</td>
<td>223.04</td>
<td>821.222</td>
</tr>
<tr>
<td>7.55125</td>
<td>0.048125</td>
<td>260.22</td>
<td>958.193</td>
</tr>
<tr>
<td>8.63(Fracture load)</td>
<td>0.055(Final extension)</td>
<td>297.395</td>
<td>1094.963</td>
</tr>
</tbody>
</table>

Final length of specimen \( L_f \) = 53 mm
Elongation = \( \frac{L_f - L_o}{L_o} \times 100 = 5.514\% \)

### 4.1.4 Quenched in Brine

**Observations**

Original length of specimen \( L_o \) = 50.24 mm
Diameter = 6.16 mm
Area = 29.787296 mm\(^2\)

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain ( \times 10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0.001875</td>
<td>13.43</td>
<td>37.321</td>
</tr>
<tr>
<td>0.8</td>
<td>0.00375</td>
<td>26.86</td>
<td>74.642</td>
</tr>
<tr>
<td>1.2</td>
<td>0.005625</td>
<td>40.29</td>
<td>111.963</td>
</tr>
<tr>
<td>1.6</td>
<td>0.0075</td>
<td>53.71</td>
<td>149.283</td>
</tr>
<tr>
<td>2.0</td>
<td>0.009375</td>
<td>67.14</td>
<td>186.6043</td>
</tr>
<tr>
<td>2.4</td>
<td>0.01125</td>
<td>80.57</td>
<td>223.925</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain ( \times 10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.56</td>
<td>0.002875</td>
<td>19.046</td>
<td>54.716</td>
</tr>
<tr>
<td>1.12</td>
<td>0.00575</td>
<td>38.09</td>
<td>109.524</td>
</tr>
<tr>
<td>1.68</td>
<td>0.008625</td>
<td>57.14</td>
<td>164.286</td>
</tr>
<tr>
<td>2.24</td>
<td>0.01115</td>
<td>76.186</td>
<td>219.048</td>
</tr>
<tr>
<td>2.80</td>
<td>0.014375</td>
<td>95.23</td>
<td>273.8095</td>
</tr>
<tr>
<td>3.36</td>
<td>0.01725</td>
<td>114.28</td>
<td>328.571</td>
</tr>
<tr>
<td>3.92</td>
<td>0.020125</td>
<td>133.26</td>
<td>383.333</td>
</tr>
<tr>
<td>4.48(Fracture load)</td>
<td>0.023(Final extension)</td>
<td>125.37</td>
<td>438.095</td>
</tr>
</tbody>
</table>
Final Length of Specimen ($L_f$) = 50.44 mm
Elongation = \frac{L_f - L_o}{L_o} \times 100 = 0.398% 

4.1.5 Quenched in Ice water

Observations
Original length of specimen ($L_o$) = 52.5 mm
Diameter = 6.16 mm
Area = 29.018624 mm$^2$

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain \times 10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.20625</td>
<td>0.000625</td>
<td>6.9258</td>
<td>11.90476</td>
</tr>
<tr>
<td>0.4125</td>
<td>0.00125</td>
<td>13.841</td>
<td>23.80952</td>
</tr>
<tr>
<td>0.61875</td>
<td>0.001875</td>
<td>20.761</td>
<td>35.71429</td>
</tr>
<tr>
<td>0.825</td>
<td>0.0025</td>
<td>27.68</td>
<td>47.619</td>
</tr>
<tr>
<td>1.03125</td>
<td>0.003125</td>
<td>34.603</td>
<td>59.52381</td>
</tr>
<tr>
<td>1.2375</td>
<td>0.00375</td>
<td>41.5235</td>
<td>71.42857</td>
</tr>
<tr>
<td>1.44375</td>
<td>0.004375</td>
<td>48.444</td>
<td>83.3333</td>
</tr>
<tr>
<td>1.65(Fracture load)</td>
<td>0.005(Final extension)</td>
<td>55.365</td>
<td>95.2381</td>
</tr>
</tbody>
</table>

Final Length of Specimen ($L_f$) = 52.65 mm
Elongation = \frac{L_f - L_o}{L_o} \times 100 = 0.2857% 

4.1.6 Martempered

Observations
Original length of specimen ($L_o$) = 51mm
Diameter = 6.12 mm
Area = 29.4166 mm$^2$

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain \times 10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.825</td>
<td>0.004375</td>
<td>28.045</td>
<td>85.7843</td>
</tr>
<tr>
<td>1.65</td>
<td>0.00875</td>
<td>56.091</td>
<td>171.5686</td>
</tr>
<tr>
<td>2.475</td>
<td>0.013125</td>
<td>84.136</td>
<td>257.3529</td>
</tr>
<tr>
<td>3.3</td>
<td>0.0175</td>
<td>112.18</td>
<td>343.137</td>
</tr>
<tr>
<td>4.125</td>
<td>0.021875</td>
<td>140.23</td>
<td>428.9216</td>
</tr>
<tr>
<td>4.95</td>
<td>0.02625</td>
<td>168.27</td>
<td>514.7059</td>
</tr>
<tr>
<td>5.775</td>
<td>0.030625</td>
<td>196.32</td>
<td>600.4902</td>
</tr>
<tr>
<td>6.6(Fracture load)</td>
<td>0.035 (Final extension)</td>
<td>224.36</td>
<td>686.2745</td>
</tr>
</tbody>
</table>

Final length of the specimen ($L_f$) = 51.6 mm
Elongation = \( \frac{L_f - L_o}{L_o} \times 100 = 1.176\% \)

4.1.7 Austempered

**Observations**

Original length of specimen (\( L_o \)) = 50.5 mm

Diameter = 6.10 mm

Area = 29.2246 mm\(^2\)

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>Extension (mm)</th>
<th>Stress (MPa)</th>
<th>Strain ( \times 10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5625</td>
<td>0.005625</td>
<td>19.247</td>
<td>111.3861</td>
</tr>
<tr>
<td>1.125</td>
<td>0.01125</td>
<td>38.495</td>
<td>222.772</td>
</tr>
<tr>
<td>1.6875</td>
<td>0.016875</td>
<td>57.742</td>
<td>334.15843</td>
</tr>
<tr>
<td>2.25</td>
<td>0.0225</td>
<td>76.99</td>
<td>445.544</td>
</tr>
<tr>
<td>2.8125</td>
<td>0.028125</td>
<td>96.237</td>
<td>556.93069</td>
</tr>
<tr>
<td>3.375</td>
<td>0.03375</td>
<td>115.485</td>
<td>668.3168</td>
</tr>
<tr>
<td>3.9375</td>
<td>0.039375</td>
<td>134.73</td>
<td>779.70297</td>
</tr>
<tr>
<td>4.5 (Fracture load)</td>
<td>0.045 (Final extension)</td>
<td>153.9799</td>
<td>891.089</td>
</tr>
</tbody>
</table>

Final Length of the specimen (\( L_f \)) = 51.00 mm

Elongation = \( \frac{L_f - L_o}{L_o} \times 100 = 0.980\% \)

4.2. HARDNESS TESTING

4.2.1 Rockwell Hardness Testing

**Observations**

Minor load = 10kg

Major load = 150kg

Scale to be used = C (black)

Indenter used = Diamond cone

Time = 10-15 sec

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Treatments</th>
<th>HR(_C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Untreated</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Water quenched</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>Oil quenched</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Brine quenched</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>Ice water quenched</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>Martempered</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Austempered</td>
<td>10</td>
</tr>
</tbody>
</table>
4.3 METALLOGRAPHY

Following results were obtained from metallographic observations of piston rings samples under metallurgical microscope.

4.3.1 Untreated

![Microstructure of as cast Gray Cast Iron Sample (150X)](image)

**Fig 4.1** Microstructure of as cast Gray Cast Iron Sample (150X)
Interdendritic Graphite flakes (black) in a matrix of pearlite (gray) with cementite along grain boundaries (white net work) and small amount of massive ferrite (white)
**Fig 4.2** Same as Fig-4.1 but at 400X. Interdendritic Distorted Graphite flakes (black) in a matrix of pearlite (gray) with cementite along grain boundaries (white net work) and small amount of massive ferrite (white)

4.3.2 Quenched in Water

**Fig 4.3** Microstructure of Water Quenched Gray Cast Iron Sample (150X) Distorted Graphite flakes (black) in a matrix of martensite (gray) and retained austenite (white)
**Fig 4.4** Same as Fig-4.3 but at 400X Distorted Graphite flakes (black) in a matrix of martensite (gray) and retained austenite (white)

4.3.3 Quenched in Oil

**Fig 4.5** Microstructure of Oil Quenched Gray Cast Iron Sample (150X)
Distorted Graphite flakes (black) in a matrix of very fine pearlite (gray), some carbide particles (light outlined) and small amount of retained austenite (white)
**Fig 4.6** Same as Fig 4.5 but at 400X Distorted Graphite flakes (black) in a matrix of very fine pearlite (gray), some carbide particles (light outlined) and retained austenite (white)

4.3.4 Quenched in Brine

**Fig 4.7** Microstructure of Brine Quenched Gray Cast Iron Sample (150X) Distorted Graphite flakes (black) in a matrix of martensite (gray) and small amount of retained austenite (white)
Fig 4.8 Same as Fig 4.7 but at 400X Distorted Graphite flakes (black) in a matrix of martensite (gray) and small amount of retained austenite (white)

Quench Cracks

Fig 4.9 Microstructure of a crack produced in brine quenched Gray Cast Iron Sample (400X) (Micrograph of the surface of the specimen) Crack is running all along grain boundaries through out the structure.
Fig 4.10 Same as Fig 4.9 but from lower section (400X) Crack is running all along grain boundaries throughout the structure. (Intergranular crack)

4.3.5 Quenched in Ice Water

Fig 4.10 Microstructure of Ice Water Quenched Gray Cast Iron Sample (150X) Distorted Graphite flakes (black) in a matrix of martensite (gray) and retained austenite (white)
**Fig 4.11** Same as Fig-4.10 but at 400X Distorted Graphite flakes (black) in a matrix of martensite (gray) and retained austenite (white)

4.3.6 Martempered

**Fig 4.12** Microstructure of Martempered Gray Cast Iron Sample (150X) Distorted Graphite flakes (black) in a matrix of ferrite (white) and fine pearlite (gray)
Fig 4.13 Same as Fig 4.12 but at 400X. Distorted Graphite flakes (black) in a matrix of ferrite (white) and fine pearlite (gray).

4.3.7 Austempered

Fig 4.13 Microstructure of Austempered Gray Cast Iron Sample (150X) Distorted Graphite flakes (black) in a matrix of ferrite (white) and coarse pearlite (gray).
Fig 4.13 Same as Fig-4.12 but at 400X Distorted Graphite flakes (black) in a matrix of ferrite (white) and coarse pearlite (gray).
Microstructure shows the graphite flakes in a matrix of ferrite and pearlite with cementite along grain boundaries. Dark areas are pearlite while light areas are massive ferrite.
5.1 TENSILE TESTING

1. Untreated

This specimen has shown value of UTS = 287.073 MPa which is quite in agreement with the value found in literature (295 MPa) [3] which indicates that material selected (gray cast iron) is giving good properties when tensile tested as expected theoretically. Moreover material is also showing very little elongation, which indicates that cast irons usually do not yield. This happens due to the

a) Presence of graphite flakes, which create notching effect at the tips of the flakes and reduces the matrix to flake compatibility and thus reduces the notch toughness of material and

b) Brittle cementite network all along grain boundaries which reduces the strength of grain boundaries and hence the strength of the bulk material.

2. Quenched in water

This specimen has shown value of UTS = 125.37 MPa, which indicates that material, has undergone a decrease in tensile strength when quenched in water from its original value in non-treated condition. Also material has shown a decrease in elongation value as well which indicates that material has very negligibly yielded which is of no practical use. This probably has happened due to the development of internal stresses in the part when quenched from above the austenitizing temperature along with a martensitic structure, which caused a profound decrease in the overall strength and yielding of the material by increasing the brittleness of already brittle gray cast iron. However the main factor contributing to this behavior is development of internal stresses.

3. Quenched in Oil

This specimen has shown value of UTS = 297.395 MPa along with a very prominent value of elongation (5.514%), which indicates that material, has experienced a small increase in its tensile strength when quenched in oil from its original value in non-treated condition. This might have happened due to the formation of some tough structure such as very fine pearlite in the microstructure. This toughness and strength is imparted because of shortening of vapor blanket stage during heat removal in quenching from specimen surface, which have caused the formation of very fine pearlite in whole of the cross-section. This phase have increased the material’s ability to absorb more energy before fracture i-e it has increased material’s toughness and have made it more resistant to shock loads. Moreover it has also little increased the stiffness of material i-e material’s
ability to resist any permanent change in its shape thus increased its life as well as performance.

4. Quenched in Brine

This specimen has shown value of UTS = 107.43MPa along with a elongation value of 0.389% which indicates that material has undergone same type of change in its microstructure as has been experienced by specimen number 2 i-e material have developed martensitic structure but partially, and have also developed some isolated patches of retained austenite which have decreased the overall strength of material (latter proved true from hardness values and metallography) and also effected its elongation value (decrease in elongation value is observed). This type of structure has also decreased other properties of the material such as toughness, stiffness, hardness etc. This type of behavior may also be the result of development of internal stresses, which have caused an increase in brittleness of already brittle gray cast iron under tensile loads. Both the above-mentioned factors contribute towards the decrease in overall strength of the material.

5. Quenched in Ice water

This specimen has shown a very small value of UTS = 55.365MPa along with a elongation value of 0.2857% which indicates that some very brittle structure has developed in the material. This behavior is mainly caused by the development of martensite along with retained austenite in some areas, formed due to very rapid rate of heat removal from surface of the specimen during quenching, which have caused a considerable decrease in toughness and strength of the material. This profound decrease in UTS value may also have been observed due to the development of considerable amount of internal stresses throughout the cross-section due to very severe quenching conditions of ice water and decreased the strength of gray cast iron under tensile loads. Both above-mentioned factors contribute towards the decrease in overall strength of gray cast iron and also decreased its related properties (stiffness, toughness etc.)

6. Martempered

This specimen has shown a value of UTS = 224.36MPa along with a elongation value of 1.176% which is comparable to values of non-treated sample, which indicates that phases like combination a of pearlite and ferrite have formed in the microstructure of the material and have not caused any considerable change in values of treated sample from the one which was in non-treated condition. This apparent contradiction may have been caused by one of following reasons,

a) Time for the transfer of samples from one furnace to the other may have been prolonged excessively or the furnace temperature was not uniform for the whole of the cross-section and keep varying from point to point due to conduction, which have caused the formation of diffusional intermediate products such as pearlite etc. instead of 100% martensite.

b) Proper $M_s$ temperature was not used i-e a temperature above $M_s$ was used which caused the transformation of austenite to pearlite instead of 100% martensite and keep
the overall strength of the material to almost same level as was in original untreated sample.

c) Proper quenching conditions were not used i-e another furnace was used instead of proper (recommended) salt bath for martempering which have failed to create conditions of true martempering and facilitate the formation of non-martensitic products.

However major contributor was increased transfer time from one furnace to another furnace.

7. Austempered

This specimen has shown a value of UTS = 153.97MPa along with an elongation value of 0.980%, which indicates that one of following may have happened

a) Again time for the transfer of specimen from one furnace to another have increased excessively which have caused the formation of diffusional transformation products (such as pearlite, ferrite etc.) during the time interval in which specimen was in the midway between furnaces instead of proper bainite when specimen was put in to the bainitic range. Bainite did not formed because pearlite and alike have already formed.

b) Temperature for bainitic transformation was not properly maintained due to poor heat transfer conditions inside a furnace instead of good conditions in a salt bath, which in fact assisted in the formation of diffusional transformation products in the specimen.

c) Time at improper temperature was too much prolonged which helped in the softening of the part to a larger extent by the formation of diffusional products in the whole of the cross-section. i-e austenite to pearlite and ferrite transformation was approximately completely achieved with a post-softening of matrix due to increase in amount of ferrite.

5.2 HARDNESS TESTING

Variation of harness with the change of treatment and its variation on the graph shows that hardness was maximum for water quenched sample and decrease as the severity of quench decreases from brine to austempered specimens.

The hardness was found maximum in water quench sample because of the formation of martensite throughout the matrix of the specimen (one of the hardest phases which appears in IC system). This transformation is accompanied by a lattice distortion, which is the main cause of high hardness of martensite. Quenching conditions in water proves favorable for the complete or at least near complete austenite to martensite transformation. This high hardness is also the result of formation of internal stresses, which causes the development of strain in the matrix and increased hardness.

Hardness value is lower for brine sample as compared to water quenched sample due to the reason of development of small areas of non-martensitic products (such as retained austenite etc.)

Hardness value further decreases for ice water quenched & oil quenched samples respectfully. This happens due to considerable increase in percentage of non-martensitic products (retained austenite), which decreased the overall hardness of material along with its UTS value (section 5.1.5)
In the end hardness values are very low for martempered and austempered samples respectively. This again happens due to the reasons previously described (sections 5.1.6 & 5.1.7) i-e due to the formation of considerable amount of diffusional transformation products as the condition changes from martempering to austempering (i-e time increases in transformation region), because as the time is increased in transformation range more and more chances of growth of soft products increases, which lowers the hardness value and induces softness in the material.

5.3 METALLOGRAPHY

5.3.1 Untreated

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of very fine pearlite and small amount of ferrite with cementite along grain boundaries. Graphite flakes are formed in a distorted state because of the very poor control on composition and melting practice (inoculation etc.). Cementite occurs as continuous network along grain boundaries of pearlite. Small amount of massive ferrite is formed at the interface of flake and matrix due to slow cooling rate and enough amount of graphitizer (Si), which promoted the transformation of almost all the combined carbon \(\text{Fe}_3\text{C}\) to graphite creating ferrite in the matrix. Matrix formed is pearlite due to intermediate cooling rate in as cast condition in a sand mold. The values of Tensile strength 287.073MPa and Hardness 24HRc also show that the structure formed is mainly pearlite (hardness 22HRc & TS 295MPa)

5.3.2 Quenched in water

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of martensite and retained austenite. Graphite flakes again are formed in a distorted state because of the very poor control on composition and melting practice (inoculation etc.) and also due to very fast cooling rates. Martensite is formed as fine needles (plate martensite) because of the fast cooling rate of water, which depressed any diffusion assisted transformation and resulted in a diffusion less product which accounts for the very high hardness of the structure (58HRc). Martensite formed is plate martensite because plate type of martensite is formed in high carbon alloys such as cast irons. Retained austenite is formed again because of the very fast cooling rate of water, which resulted in incomplete transformation of austenite to martensite and retained the high temperature phase, austenite at room temperature (known as retained austenite). This retained austenite impairs the properties of the final product by inducing softness in structure at various places due to its low hardness (40HRc) and thus causes variation of mechanical properties (hardness) from point to point and also lowers the overall strength of the product. So, retained austenite is to be avoided in final structure, though it is not always easy, especially with very severe quenching conditions (such as in water). The values of tensile strength and hardness obtained from tensile test and hardness test (T.S 125.37MPa and 58HRc) also showed that structure formed is mainly martensite (hardness
65HRc(max.)). The low value of tensile strength is obtained because of the development of internal stresses associated with martensitic transformation, which induced brittleness in structure and lowered its tensile strength while decrease in hardness has occurred because of presence of retained austenite which causes a profound decrease in hardness due to its nature of relaxing internal stresses by plastically deforming itself (austenite is FCC) and giving way to adjacent martensite plates to adjust and arrange themselves to configuration of lower state of energy thus lowers hardness.

5.3.3 Quenched in Oil

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (Longest flakes ¼ to ½ in. in length.) in a matrix of very fine pearlite and small amount of retained austenite. Graphite flakes are formed in a distorted state because of the very poor control on composition and melting practice (inoculation etc.). Very fine pearlite is formed as very fine lamella, this happens due to relatively slow cooling rate of oil which resulted in little diffusion and assisted in formation of some diffusional products (fine pearlite) and this accounts for the high hardness of the structure (36HRc)[2][5]. Some carbides particles are formed because of incomplete transformation of some of the combined carbon (Fe₃C) to graphite during cooling. Retained austenite is formed again because of the fast cooling rate of oil, which resulted in incomplete transformation of austenite to fine pearlite and retained the high temperature phase, austenite at room temperature (known as retained austenite). This retained austenite impairs the properties of the final product by inducing softness in structure due to its low hardness (40HRc) and thus causes variation of mechanical properties (hardness) from point to point and also lowers the overall strength of the product. The values of tensile strength and hardness obtained from tensile test and hardness test (T.S 297.395MPa and 36HRc respectively) also showed that structure formed is mainly very fine pearlite (hardness 20-40HRc (20 upper/coarse pearlite, 40 lower/fine pearlite)). The little high value of tensile strength is obtained because of the inherent tough and ductile nature of fine pearlite phase, while decrease in hardness (from max. i-e 40 for fine pearlite) has occurred because of presence of retained austenite which causes a decrease in hardness due to its nature of relaxing internal stresses by plastically deforming itself (austenite is FCC) and giving way to adjacent fine pearlite plates to adjust and arrange themselves to configuration of lower state of energy thus lowers hardness. This also happens due to and little deviation of structure form ideally fine pearlite.

5.3.4 Quenched in brine

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of martensite and small amount of retained austenite. Graphite flakes are formed in a distorted state again because of the very poor control on composition and melting practice (inoculation etc.). Martensite is formed as very fine needles (plate amrtensite) because of the very fast cooling rate of brine, which depressed any diffusion assisted transformation and resulted in a diffusion less product that accounts for the very high hardness of the structure.
(54HRc). **Retained austenite** is formed again because of the very fast cooling rate of brine, which resulted in incomplete transformation of austenite to martensite and retained the high temperature phase, austenite at room temperature (known as retained austenite). This retained austenite impairs the properties of the final product by inducing softness in structure due to its low hardness (40HRc) and thus causes variation of mechanical properties (hardness) from point to point and also lowers the overall strength of the product. The values of **tensile strength** and **hardness** obtained from tensile test and hardness test (T.S 107.43MPa and 54HRc respectively) also showed that structure formed is mainly martensite (hardness 65HRc(max.)). The low value of tensile strength is obtained because of the development of internal stresses associated with martensitic transformation, which induces brittleness in structure and lowered its tensile strength, while **decrease in hardness** has occurred because of presence of retained austenite which causes a profound decrease in hardness due to its nature of relaxing internal stresses by plastically deforming itself (austenite is FCC) and giving way to adjacent martensite plates to adjust and arrange themselves to configuration of lower state of energy thus lower hardness. The **hardness** values of the brine quenched samples are even lower than the hardness values of water quenched, which is contrary to observations (brine has more severe quenching effect than water). This happened because more dispersed amount of retained austenite is formed in brine quenching which causes more relaxing of the internal stresses and thus lowers overall hardness.

**Crack:** A crack is produced in brine quenched specimen. It started from surface and runs throughout the cross-section of the specimen transverse to the longitudinal axis of the specimen. This is **intergranular** quench crack, which is produced only on the surface of the specimen during quenching in brine. The crack is produced because of very fast rate of heat removal from surface of the specimen by quenchant (brine), which results in very quick formation of martensite (a hard and brittle phase) on the surface while there was still austenite in the core, as core transformed to martensite it expanded and thus produced tensile stresses in the surface which has already transformed to hard and brittle martensite it did not accommodated the expansion thus it cracked and produced what are known as quench cracks.

The regions adjacent to crack on either side are 100% martensite due to very severe quenching rates over there due to **seeping in** of the quenchant in the crack and continuous breaking up of the vapor blanket on the surface of the specimen, which further increased the cooling rate and promoted the formation of the martensite.

### 5.3.5 Quenched in ice water

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of martensite and a large amount of retained austenite. **Graphite flakes** are formed in a distorted state because of the very poor control on composition and melting practice (inoculation etc.). **Martensite** is formed as fine needles (plate martensite) because of the fast cooling rate of ice water, which depressed any diffusional transformation and resulted in a diffusion less product that accounts for the very high hardness of the structure (50HRc). **Retained austenite** is formed again because of the very fast cooling rate of ice water, which resulted in incomplete transformation of austenite to martensite and retained the high
temperature phase, austenite at room temperature (known as retained austenite). Here again this retained austenite impairs the properties of the final product by inducing softness in structure at various places due to its low hardness (40HRc) and thus causes variation of mechanical properties (hardness) from point to point and also lowers the overall strength of the product. The values of tensile strength and hardness obtained form tensile test and hardness test (T.S 55.365MPa and 50HRc respectively) also showed that structure formed is mainly martensite (hardness 65HRc(max.)). The very low value of tensile strength is obtained because of the development of large amount of internal stresses associated with martensitic transformation, which induces high brittleness in structure and lowered its tensile strength to a very large extent, while decrease in hardness from expected maximum (65HRc) has occurred because of presence of retained austenite which again causes a profound decrease in hardness due to its nature of relaxing internal stresses by plastically deforming itself (austenite is FCC) and giving way to adjacent martensite plates to adjust and arrange themselves to configuration of lower state of energy thus lower hardness.

5.3.6 Martempered

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of pearlite and ferrite. Graphite flakes are formed in a distorted state again because of the very poor control on composition and melting practice (inoculation etc.). Pearlite is formed as fine lamella because of the intermediate to fast cooling rate of air, which facilitated the austenite to pearlite transformation by diffusion. This nucleation of pearlite started during the gap in which specimen was shifted from austenitising furnace to martempring furnace and it continued during the holding in the temperature range of 200ºC in martempering furnace. This presence of pearlite accounts for low hardness of the structure (13HRc). Ferrite is formed during the period in which specimen was placed in martempering furnace at 200ºC. The prolonged holding of the austenitized specimen at this temperature started the nucleation of ferrite and its growth continued during the period of holding. The values of tensile strength and hardness obtained form tensile test and hardness test (T.S 224.36MPa and 13HRc respectively) also showed that structure formed is mainly pearlite (hardness 20HRc(max.) of 100% pearlite). The decrease in hardness value from maximum is attributed to the fact that ferrite is also present which is a soft phase (0HRc or 90HRb) that decreased the overall hardness of the structure. The value of tensile strength 224.36MPa also suggests that structure formed is pearlite and ferrite because it conforms to the tensile strength values in literature [3].

5.3.7 Austempered

This microstructure showed small distorted graphite flakes (Type B, rosette groupings, random) of rating 5 (longest flakes ¼ to ½ in. in length.) in a matrix of coarse pearlite and ferrite. Graphite flakes are again formed in a distorted state in this structure because of the very poor control on composition and melting practice (inoculation etc.). Pearlite is formed as coarse lamella because of the intermediate to fast cooling rate of air, which facilitated the austenite to pearlite transformation by diffusion. The nucleation of pearlite
started during the gap in which specimen was shifted from austenitising furnace to austempering furnace and its growth continued during the holding in the temperature range of 300-400°C in austempering furnace. This presence of pearlite accounts for low hardness of the structure (10HRc). Ferrite is formed during the period in which specimen was placed in austempering furnace at 300-400°C. The prolonged holding of the austenitized specimen at this temperature started the nucleation of ferrite and its growth continued during the period of holding. Further this prolonged holding of approximately 25 minutes assisted the formation of coarse pearlite by diffusion and growth. The values of tensile strength and hardness obtained from tensile test and hardness test (T.S 153.98MPa and 10HRc respectively) also showed that structure formed is mainly coarse pearlite (hardness 20HRc(max.) of 100% pearlite). The decrease in hardness value from maximum is attributed to the fact that ferrite is also present which is a soft phase (0HRc or 90HRb) that decreased the overall hardness of the structure. The value of tensile strength 153.98MPa also suggest that structure formed is pearlite and ferrite because it conforms to the tensile strength values found in literature [3]

**Graphite Flakes**

The decrease or deviation from expected, or theoretical tensile strength and hardness values of almost all samples is also attributed to abnormal flake structure (Type B), which results in poor strength and wear resistance properties in all the specimens irrespective of the heat treatment given.
Microstructure shows flakes of graphite in a matrix of fine pearlite and retained austenite. Gray areas are fine pearlite while white areas are retained austenite. This structure gives highest TS value.

Conclusion
Following conclusions can be drawn out from above results and discussion

6.1 Tensile Strength

- Oil Quenched samples has developed maximum tensile strength (UTS = 297.395MPa). This treatment have increased the UTS value of gray cast iron from 287.037 MPa in untreated condition to 297.395 MPa after treatment, approximate 1.15 times increase in value, which resulted in the some improvement in properties (such as wear, life, efficiency etc. of gray cast iron piston ring).
- Ice water Quenched sample have developed minimum tensile strength (UTS = 55.365 MPa). Approximately 5 times decrease in UTS value have occurred due to ice water quenching of gray cast iron
- Martempered and Austempered samples on the other hand surprisingly have not developed high UTS value. Due to poor martempering and austempering practices.
- All other samples i-e those which have gone through water quenching, brine quenching etc. have undergone actually a decrease in their UTS value from the value in untreated condition due to development of internal stresses.
- Any of the cast iron samples did not yielded to an appreciable extent, which indicates the absence of yielding in cast irons.

So it is recommended that for improvement in mechanical properties of gray cast iron piston rings either quenching in oil should be used or proper martempring or austemepring practice should be adopted.

6.2 Hardness

Hardness values shows that hard structures have formed during transformation when samples were water quenched but internal stresses have also developed along with them and these hard structures disappeared as the severity of quench decreased so, for obtaining high hardness values sever quenching conditions are recommended provided that internal stresses does not impair other properties.

6.3 Metallography

Metallography showed that

a) Distorted graphite flake structure is formed in all the specimens.

This happens due to
- Improper composition control.
- Insufficient time for solidification in the mold (i-e very fast cooling rate).
- Improper inoculation practice.
- Insufficient superheating of the melt.
This abnormal flake structure imparts very poor strength and wear resistance properties to final product. So, if above mentioned parameters are controlled properly, proper graphite flake structure can be obtained and a very profound improvement in mechanical properties could be achieved [6].

b) **Retained austenite** is formed in almost all the specimens, which were quenched. This happens due to incomplete transformation of austenite to martensite during quenching due to very fast cooling rates. This retained austenite can seriously impair the final properties of the product (e.g. it can induce softness, lowers the overall strength of the structure). So utmost effort should be made to avoid retained austenite in final structure, though it is not always easy, especially with severe quenching conditions (such as in water etc.). However retained austenite if formed could be eliminated by sub-zero treatment [2]

c) **Cracking.** Specimen quenched in brine showed cracking at surface this cracking has occurred because of very severe quenching rates of brine. So, proper quenchants should be used to avoid cracks [2]

d) **Poor Martempering and Austempering.** Specimen martempered and austempered did not develop the required or anticipated structures because of poor martempering and austempering practices/conditions. So proper martempering and austempering practices should be used (salt bath treatment) to achieve proper results [8][2].
BIBLIOGRAPHY

Books


Web Sites

1. www.riken.co.jp
2. www.kesintl.com
3. www.indiamart.com/rimaco
4. www.totalseal.com
5. www.carleysoftware.com/piston rings
6. www.ss wesco.com
7. www.engine tech.com
8. www.family car.com
9. www.key-to-steel.com
10. www.parker.com
Quenched in water (Load Vs Extension)
Quenched in Oil (Stress Vs Strain)
Quenched In Brine (Stress Vs Strain)

- Stress (MPa)
- Strain (x10 x10^-6)

- Graph showing a linear relationship between stress and strain for quenched in brine conditions.