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# Heat Treatment of Medium Carbon Steel and Evaluation Of Micro hardness and Wear Resistance for Automotive Applications

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***ABSTRACT****:- The objective of the project is to evaluate the microhardness and wear resistance of medium carbon steel. medium carbon steel is extensively used in structural and automotive applications due to its balancing properties of hardness, wear resistance, ductility and strength. The main aim of heat treatment is to change its mechanical properties such as hardness, strength and other tribological properties. Cylindrical specimens were prepared using lathe machine of required dimensions. The surface treatments such as gas nitriding, liquid nitriding and induction hardening were employed to evaluate the mild carbon steel properties. Three specimens each is subjected to different temperatures 500°C, 550°C, 600°C as same for all surface treatments but varying soaking time. The heat treatments are followed by quenching with different medium and tempering under same temperature for all the surface treatment process. XRD test is taken for layer formation. Microhardness values are tabulated from vickers microhardness testing machine. The wear resistance is calculated with the help of pin-on- disc apparatus. The wear test parameters were taken as sliding velocity (V) 1.5 m/s, normal force (N) 5 N and sliding distance (S) 600 m. The values obtained are compared within the surface treatment processes. The optimum valve obtained shows, the temperature and quenching medium has an significant role in deciding the properties of specimen i.e. high hardness and wear resistance.*

***Keywords:-*** *Gas nitriding, hardness, induction hardening, liquid nitriding, medium carbon steel, wear resistance.*

## I. INTRODUCTION

The strength of steel is influenced by its microstructure (the type of crystal patterns). The microstructure is controlled by the arrangement of the atoms of the various elements in the steel. Heating and cooling of the steel influences this atomic arrangement [1]. The increased use of iron and steel content of a modern vehicle continues to be as high as 70%. Metallic materials are ideally suited for applications in heavily stressed components that require high durability. The degree of functionality and component performance is strongly tied to the effectiveness of the processing technology deployed for a given application. Body parts are usually produced from steel sheets that have been rolled and thermally processed to create the desired properties [2]. The medium carbon steel finds extensive use with surface treatments.

The process heat treatment is carried out first by heating the metal and then cooling it in water, oil and brine water. The purpose of heat treatment is to change the grain size, to modify the structure of the material and relive the stress set up in the material. The various heat treatment process are annealing, normalizing, hardening, austempering, mar tempering, tempering and surface hardening Application such as gears, kicker rods, bolts are made of medium carbon alloy steels like EN-24 steel [3].

Mild steel is the least expensive of all steel and the most common steel used. Used in nearly every type of product created from steel, it is weldable, very hard. Containing a maximum of 0.29% carbon, this type of steel is able to be magnetized and used in almost any project that requires a vast amount of metal [4].

**1.1 Nitriding**

Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range (500 to 600°C) while it is in the ferrite condition. Thus, nitriding is similar to carburizing in that surface composition is altered, but different in that nitrogen is added into ferrite instead of austenite. Because nitriding does not involve heating into the austenite phase field and a subsequent quench to form martensite, nitriding can be accomplished with a minimum of distortion and with excellent dimensional control. In this process pure ammonia dissociates by the reaction.

$$NH_3 = 3H + N \quad \text{--------------------------} \qquad (1.1)$$

The atomic nitrogen thus formed diffuses into the steel. In addition to providing outstanding wear resistance, the nitride layer increases the corrosion resistance of steel in moist atmosphere and improves hardness. Practically only alloy steels are subjected to nitriding [5].

**1.2 Flame hardening**

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

**1.3 Tempering**

After the hardening treatment is applied, steel is often harder than needed and is too brittle for most practical uses. Also, severe internal stresses are set up during the rapid cooling from the hardening temperature. To relieve the internal stresses and reduce brittleness, tempering the steel is carried out. Tempering consists of heating the steel to a specific temperature (below its hardening temperature), holding it at that temperature for the required length of time, and then cooling it, usually instill air. The resultant strength, hardness, and ductility depend on the temperature to which the steel is heated during the tempering process. The purpose of tempering is to reduce the brittleness imparted by hardening and to produce definite physical properties within the steel. Tempering always follows, never precedes, the hardening operation. Besides reducing brittleness, tempering softens the steel. That is unavoidable, and the amount of hardness that is lost depends on the temperature that the steel is heated to during the tempering process. That is true of all steels except high-speed steel [5].

**1.4 Wear**

Wear is commonly defined as the undesirable deterioration of a component by the removal of material from its surface. It occurs by displacement and detachment of particles from surface. The mechanical properties of steel are sharply reduced due to wear. The wear of material may be due to the friction of metals against each other, eroding effect of liquid and gaseous media, scratching of solid particles from the surface and other surface phenomena. In laboratory tests, wear are usually determined by weight loss in a material and wear resistance is characterized by the loss in weight per unit area per unit time. Wear volume is calculated using pin-on-disc apparatus [5].

**1.5 Hardness**

Hardness is the property of a material to resist permanent indentation. Because there are several methods of measuring hardness, the hardness of a material is always specified in terms of the particular test that was used to measure this property. Rockwell, Vickers, or Brinell are some of the methods of testing. Of these tests, Rockwell is the one most frequently used. Vickers microhardness testing machine is used to find the hardness of the different surface treated specimens [5].

**1.6 Objective of the work**

The aim of this present work is to improve the mechanical properties and wear resistance of the medium carbon steel by using diffusion and applied energy of surface hardening technique. In this connection the following studies were aimed to be carried out.

1. Stress relieving using Annealing.
2. Nitriding - gas and liquid, induction hardening under different temperature and soaking hours.
3. XRD analysis for confirmatory of layer formation.
4. Micro hardness and dry sliding wear test for evaluation.

**1.7 Literature survey**

The investigation on the mechanical and wear properties of medium carbon steel component under different condition have been explored .The below literature survey will rope the various studies made on medium carbon steel under varying surface treatments.

Jaykant gupta (2009), studied investigation the mechanical and wear behaviours of mild steels carburized at different temperature range of 850, 900 and 950$^{O}$ C have been studied and it is found that the simple heat treatments greatly improves the hardness, tensile strength and wear resistance of the mild steels. Sanjib kumar jaypuria(2009), investigated the low carbon steel by carrying out experiments of harness and ultimate tensile strength is done to get idea about heat treated low carbon steel, which has extensive uses in all industrial and scientific fields to improve ductility, to improve toughness, strength, hardness and tensile strength and to relive internal stress developed in the material. Mayank et al (2014), reviewed on corrosion behaviour of ferritic stainless steel. Awedo et al (2015), observed Effects of Continuous Cooling On Impact and Micro Structural Properties of Low Carbon Steel Welded Plate. Karthikeyan et al (2014), investigated the Effect of Subzero Treatment on Microstructure and Material Properties of EN24 Steel. Gary doyon et al (2013), observed that reducing the amount of heat generated within a part and providing uniform heating without applying force go a long way in controlling part distortion during induction hardening. Kiyoshi funatani (2004), overviewed Selected aspects of heat treatment and surface modification technologies including future technological possibilities, of relevance to the automotive industry. Jisen Wang et al (2005), presented the results of nitriding of medium carbon steel at a low temperature of 573K by using the surface-alternating current nanocrystalline treatment (SACNT), which was much lower than conventional nitriding temperature (about 773 K). The surface microhardness measurements indicated that the compound layer exhibited a much greater hardness of about 560 Hv. The thickness of nitride layer was about 200 µm. Seyda Polat et al (2012), applied gas nitriding process for H13 tool steel to modify the surface and studied its characterization. Ferit Ficici et al (2011), studied the wear behavior of boronized AISI 1040 steel by using pin on disc apparatus. Wear test specimen were machined from boronized samples to form cylindrical pins having a diameter of 6 mm and a length of 10 mm. The dry sliding wear tests were conducted using a pin-on-disc apparatus at room temperature regarding the ASTM G99-95 standards. Amit Kohli et al (2011), studied an effective procedure of response surface methodology (RSM) has been utilized for finding the optimal values of process parameters while induction hardening of AISI 1040 steel. Wear resistance of induction hardened AISI 1040 steel were greatly improved by choosing the optimal parameter values for induction hardening treatment. Michael J. Schneider, et al (2013), revised the introduction to surface hardening of steels.

Most of this investigation had been made on study of micro structure and mechanical properties. But the combining and comparing of mechanical and tribological properties within same specimen under different temperature and same soaking time and also comparison with other surface treatment process were not studied. This paper will explore the areas of surface treatments that are significant for automotive applications. Figure 2.1 shows the sample EN8 taken for experimentation.

## II. EXPERIMENTAL PROCEDURE

**2.1 Material selection and preparation**

Material EN8 is used for experimentation of diameter 20 mm and length 500mm. Primarily annealing process of the material for 1 hour at 800 ºC to remove the stress followed by surface treatments and tests such as vicker s hardness test, dry sliding abrasive wear test and XRD analysis was performed on the selected medium carbon steel.

**2.2 Surface hardening of steel specimens**

The three test specimen samples made up of medium carbon steel for testing of hardness and wear properties were subjected to gas nitriding, liquid nitriding and induction hardening process.

**2.2.1 Gas nitriding process**

Gas nitriding is one of the most efficient methods used to enhance the surface properties of steel. The temperature range of 500, 550 and 600 °C with the soaking time of 10 hours by this way the medium carbon steel samples gets nitrided and then they were air quenched .

**2.2.2 Liquid nitriding process**

Liquid nitriding is made of a mixture of sodium and potassium salts. The sodium salt, which comprises 60 to 70 (by weight) of the total mixture, consists of 97.5% NaCN, 1.5% $Na_2CO_3$ and 1% NaCNO. The potassium salts, 30 to 40% (by weight) of the mixture, consist of 95% KCN, 0.5% $K_2CO_3$, 1.75% KCNO and

0.6% KCL. The operating temperature of salt bath was 500, 550 and 600 °C with soaking time of 2 hours. Then it was water (pH-7 balanced) quenched

**2.2.3 Induction hardening process**

A source of high frequency electricity has been used to drive a large alternating current through a copper coil. Induction temperature was 500, 550 and 600°C. It was controlled by setting the various process parameters. The table 2.1 shows the process controls of induction hardening process. The process parameters are listed for carrying out the process under controlled environment. Figure 2.2 shows the schematic representation of induction hardening.

**Table 2.1 Process Control of Induction Hardening Process**

| PROCESS PARAMETERS | CORRESPONDING VALUES |
|---|---|
| **Power** | 35 KW |
| **Dowell time** | 0.05 seconds |
| **Speed** | 25 mm/s |
| **Gap between work piece and induction coil** | 2.0 mm |

**2.3 Characterization of surface hardened steel specimens**

**2.3.1 X-ray diffraction analysis (xrd)**

The thickness of the specimen 3mm for XRD. The X- ray Diffraction patterns were obtained using XPERT-PRO Diffractometer system to confirm the formation of layers on the surface of the treated steels.

**2.3.2 Micro hardness**

The microhardness was measured using a microhardness tester MITUTOYO-MVK-H1 as shown in Fig.2.3. A load of 500 g load for 10 seconds is applied on the specimen. The average value is calculated.

**Fig. 2.1 Sample Specimen**

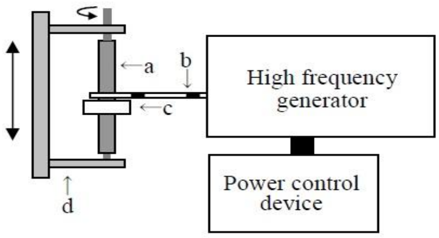



**Fig. 2.2 Induction Hardening**

**Fig. 2.3 Vicker's Microhardness Testing Machine**

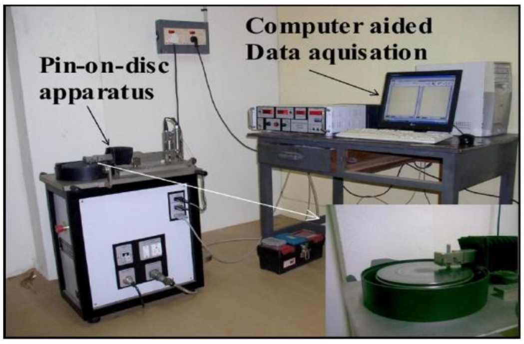



**Fig. 2.4 Pin-on-disc apparatus**

**2.3.4 Dry sliding abrasive wear test**

Cylindrical specimens of dimension with 6 mm diameter and 50 mm length were prepared using lathe machine and surface hardening techniques have done to these specimens.. Before testing, the flat surface of the specimens was abraded by using 1000 grit paper. The flat grounded specimen was mounted on the jaws of the wear testing apparatus.

#### 2.3.4.1 Conducting the experiment

The wear rate was measured using a computerized pin-on-disc wear apparatus DUCOM TR20-LE, Bangalore at room temperature according to the ASTM G99-05 standard. The wear test parameters were taken as sliding velocity (V) 1.5 m/s, normal force (N) 5 N and sliding distance (S) 600 m. The polished surface of the specimen was slid on ceramic abrasive disc. Fig. 2.4 shows the experimental setup used in this study. A computer aided data acquisition system was used to monitor the wear pattern.

**1. Wear Volume**

Wear volume is defined as ratio between weight loss to the density of the specimen.

$$\text{Wear Volume} = \frac{\text{Weight Loss}}{\text{Density of Specimen}}, \text{cm}^3 \qquad \text{---------------------------- (2.1)}$$

Density of steel specimen = 7.86 g /cm$^3$

**2. Wear Rate**

Wear rate is defined as wear volume per unit distance travelled.

$$\text{Wear Rate} = \frac{\text{Wear Volume}}{\text{Sliding Distance (S)}}, \text{cm}^2 \qquad \text{---------------------------- (2.2)}$$

**3. Wear Resistance**

Wear resistance is a reciprocal of wear rate.

$$\text{Wear Resistance} = \frac{1}{\text{Wear Rate}}, \text{cm}^{-2} \qquad \text{---------------------------- (2.3)}$$

### 2.4 Hardness and wear resistance

The gas nitriding, liquid nitiding and induction hardness is carried out with different temperatures as shown in the table 2.2, 2.3, 2.4. The values of microhardness and wear resistance are tabulated. The numerical values indicate the optimum results

**Table 2.2 Gas Nitriding condition - Evaluation of microhardness and wear resistance**

| **Gas Nitriding Condition** | | **Quenching Condition** | | **Tempering Condition** | | **Micro Hardness** | **Weight loss** | **Wear volume** | **Wear rate** | **Wear resistance** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Temp ($^O$C)** | Soak Time (Hrs) | Temp ($^O$C) from | Medium (78% $N_2$+ other gases) | Temp ($^O$C) | Soak Time (Hrs) | hv | grams | X10$^{-2}$ CM$^3$ | X 10$^{-7}$ CM$^2$ | X 10$^6$ CM$^{-2}$ |
| **500** | 10 | 500 | Air | 100 | 0.083 | 626 | 0.3513 | 4.47 | 7.45 | 1.342 |
| **550** | 10 | 550 | Air | 100 | 0.083 | 635 | 0.3356 | 4.27 | 7.11 | 1.406 |
| **600** | 10 | 600 | Air | 100 | 0.083 | 642 | 0.3246 | 4.13 | 6.88 | 1.453 |

**Table 2.3 Gas Nitriding condition - Evaluation of microhardness and wear resistance**

| **Liquid Nitriding Condition** | | **Quenching Condition** | | **Tempering Condition** | | **Micro Hardness** | **Weight loss** | **Wear volume** | **Wear rate** | **Wear resistance** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Temp ($^O$C)** | Soak Time (Hrs) | Temp ($^O$C) from | Medium (Water queched pH- 7) | Temp ($^O$C) | Soak Time (Hrs) | hv | grams | X10$^{-2}$ CM$^3$ | X 10$^{-7}$ CM$^2$ | X 10$^6$ CM$^{-2}$ |
| **500** | 2 | 500 | water | 100 | 0.083 | 532 | 0.4401 | 5.60 | 9.33 | 1.071 |
| **550** | 2 | 550 | water | 100 | 0.083 | 547 | 0.4338 | 5.52 | 9.2 | 1.086 |
| **600** | 2 | 600 | water | 100 | 0.083 | 566 | 0.4252 | 5.41 | 9.01 | 1.109 |

**Table 2.4 Induction hardening condition - Evaluation of microhardness and wear resistance**

| Induction Hardening Condition | | Quenching Condition | | Tempering Condition | | Micro Hardness | Weight loss | Wear volume | Wear rate | Wear resistance |
|---|---|---|---|---|---|---|---|---|---|---|
| **Temp ($^{O}C$)** | Soak Time (Hrs) | Temp ($^{O}C$)) from | Medium (mineral oil) | Temp ($^{O}C$) | Soak Time (Hrs) | hv | grams | $X10^{-2}$ $CM^{3}$ | $X\ 10^{-7}$ $CM^{2}$ | $X\ 10^{6}\ CM^{-2}$ |
| **500** | - | 500 | oil | 100 | 0.083 | 717 | 0.1847 | 2.35 | 3.91 | 2.557 |
| **550** | - | 550 | oil | 100 | 0.083 | 745 | 0.1351 | 1.72 | 2.86 | 3.496 |
| **600** | - | 600 | oil | 100 | 0.083 | 793 | 0.0958 | 1.22 | 2.03 | 4.926 |

**Table 2.5 Untreated condition - Evaluation of microhardness and wear resistance**

| Medium carbon steel - untreated | Micro Hardness | Weight loss | Wear volume | Wear rate | Wear resistance |
|---|---|---|---|---|---|
| **Temperature** | hv | grams | $X10^{-2}$ $CM^{3}$ | $X\ 10^{-7}$ $CM^{2}$ | $X\ 10^{6}\ CM^{-2}$ |
| **Room temperature** | 217 | 0.5596 | 7.12 | 11.8 | 0.847 |

**2.4.1 Summary**

Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range (at different temperature ranges 500, 550 and 600 $^{o}C$), while it is in the ferritic condition. Because nitriding does not involve heating into the austenite phase with quenching to form martensite, nitride components exhibit minimum distortion and excellent dimensional control. The mechanism of nitriding is generally known, but the specific reactions that occur in different steels and with different nitriding media are not always known. Nitrogen has partial solubility in iron. It can form a solid solution with ferrite at nitrogen contents up to approximately 6%. At approximately 6% N, an compound called gamma prime ($g_o$), with a composition of Fe4N, is formed. At nitrogen contents greater than 8%, the equilibrium reaction product is E compound, $Fe_3N$. Nitrided cases are stratified. The outermost surface can be all $g_o$, and, if this is the case, it is referred to as the white layer (it etches white in metallographic preparation). Such a surface layer is undesirable; it is very hard but is so brittle that it may spall in use. Usually it is removed; special nitriding processes are used to reduce this layer or make it less brittle. The E zone of the case is hardened by the formation of the , $Fe_3N$ compound, and below this layer there is some solid-solution strengthening from the nitrogen in solid solution [12].

The $Fe_3N$ (E) formed on the outer layer is harder than $Fe_4N$, which is more ductile. Controlling the formation of each of these compound layers is vital to application and degree of distortion. The depth of case and its properties are greatly dependent on the concentration and type of nitride-forming elements in the steel. In general, the higher the alloy content, the higher the case hardness. However, higher-alloying elements retard the $N_2$ diffusion rate, which slows the case depth development. Thus, nitriding requires longer cycle times to achieve a given case depth than that required for carburizing. are generally medium-carbon (quenched and tempered) steels that contain strong nitride-forming elements such as aluminum, chromium, vanadium, and molybdenum. The most significant hardening is achieved with a class of alloy steels (nitralloy type) that contain approximately 1% Al When these steels are nitrided, the aluminum forms AlN particles, which strain the ferrite lattice and create strengthening dislocations. The microstructure plays an important role in nitriding, because nitrogen can readily diffuse through ferrite, and a low carbide content favors both diffusion and case hardness [12].

Induction hardening produces surface zones that are heated and cooled very rapidly, resulting in very fine martensitic microstructures. High hardness and good wear resistance with less distortion are the results from this process [12].

**2.4.2 Benefits of nitriding**

Nitriding Hard, highly wear-resistant surface (shallow case depths); fair capacity for contact load; good bending fatigue strength; excellent resistance to seizure; excellent dimensional control possible; good freedom from quench cracking (during pretreatment); medium-to-high-cost steels required; medium capital investment required; improved salt corrosion resistance [12].

### 2.4.3 Benefits of induction hardening

Hard, highly wear-resistant surface (deep case depths); good capacity for contact load; good bending fatigue strength; fair resistance to seizure; fair dimensional control possible; fair freedom from quench cracking; low-cost steels usually satisfactory; medium capital investment required [12].

### 2.5 Automotive application

**Table 3.6 Automotive application of Heat treated components [2][6]**

| Sl.No | Types of heat treatment | Purpose | Typical Components |
|---|---|---|---|
| 1 | Annealing | Softening, and removing residual stress | 1. Forged blanks for gearing<br>2. Miscellaneous parts |
| 2 | Isothermal Annealing | Transformation control hardness and micro-structure for machining | 1. Machinability control |
| 3 | Nitriding<br><br>Case depth :<br>125 µm–0.75 mm (gas)<br>2.5 µm–0.75 mm (liquid) | Diffuse nitrogen, carbon and oxygen depending to impart wear resistant nitride layers at surface and improve hardness and strength | 1. Cam shafts<br>2. Oil pump gears<br>3. Valves<br>4. Brake pad liner plates<br>5. A/T gears |
| 4 | Induction hardening<br><br>Case depth :<br>250 to 750 µm | Heat up by inductive power and quench to get hard case locally | 1.Jouranals<br>2. Pins<br>3. Cam shafts<br>4. Drive shafts<br>4. Steering Knuckles |
| 5 | Induction tempering | Heat up by inductive power and slow cool to soften heated area. | 1. Thread area of shafts. |
| 6 | Quench and Temper | Optimize hardness for strength and toughness | 1. Fastners<br>2. Rods<br>3. Arms<br>4. Cast iron brackets<br>5. High carbon springs |

Table 3.6 shows the various types of heat treatments employed for the automotive components for hardness and wear resistance. Mild carbon steel forms the major share in the automotive applications.

## III. RESULTS AND DISCUSSION

The chemical composition of the specimen taken into consideration has verified. The medium carbon steel was subjected to various surface treatment process such as gas nitriding, liquid nitriding and induction hardening. The results obtained for microhardness, wear are discussed below.

### 3.1 Chemical composition of study material

Optical emission spectrometry in Roots Metrological Laboratories, gave the following results , which was compared with the standard specification. The chemical composition of the base material obtained by Optical Emission Spectrometry is presented in Table 3.1

**Table 3.1 Chemical Composition of EN8 Material**

| Elements | C | Si | Mn | P | S | Cr | Ni | Co | Fe |
|---|---|---|---|---|---|---|---|---|---|
| **Wt %** | 0.424 | 0.206 | 0.770 | 0.013 | 0.020 | 0.013 | 0.006 | 0.15 | 98.4 |

### 3.2 X-ray diffraction test

The XRD pattern of sample after nitriding was shown in Fig.3.1-3.2. The results shown that nitriding with r needles formation at the begining of the process and saturated whereas ε occured at later stages

### 3.3 Microstructural analysis

Figures 3.3 to 3.5 show the optical photomicrograph of diffusion zones of gas nitrided, liquid nitrided and induction hardened steels. Three distinct regions were identified are compound layer, diffusion zone and core is not affected from nitrogen. The compound layer consists of epsilon phase ($\varepsilon$-$Fe_2$-3N), gamma phase ($\gamma$ $Fe_4N$) or their mixture ($\varepsilon+\gamma$). The nitriding potential of $NH_3$- $H_2$ atmosphere directly affects the composition and growth kinetics of nitride layers. It is possible to obtain the formation of layers of predictable phase composition, thickness of particular zones and surface nitrogen concentrations, by process control.

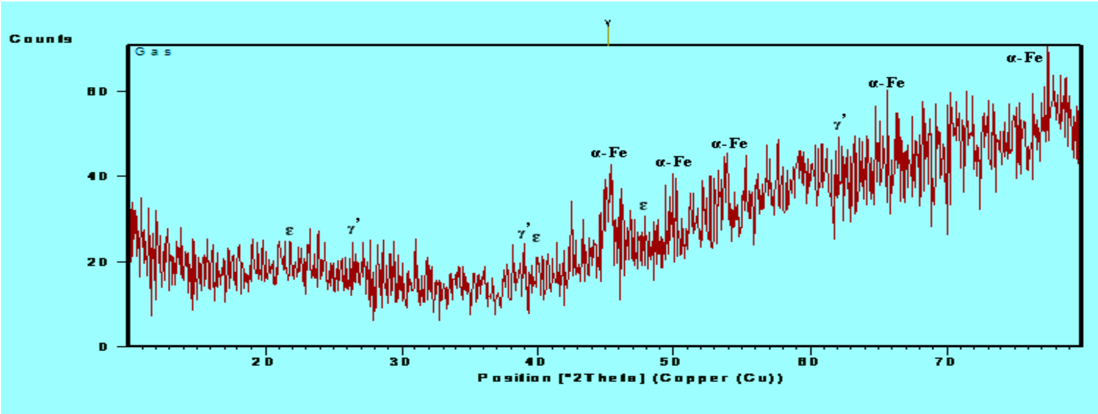
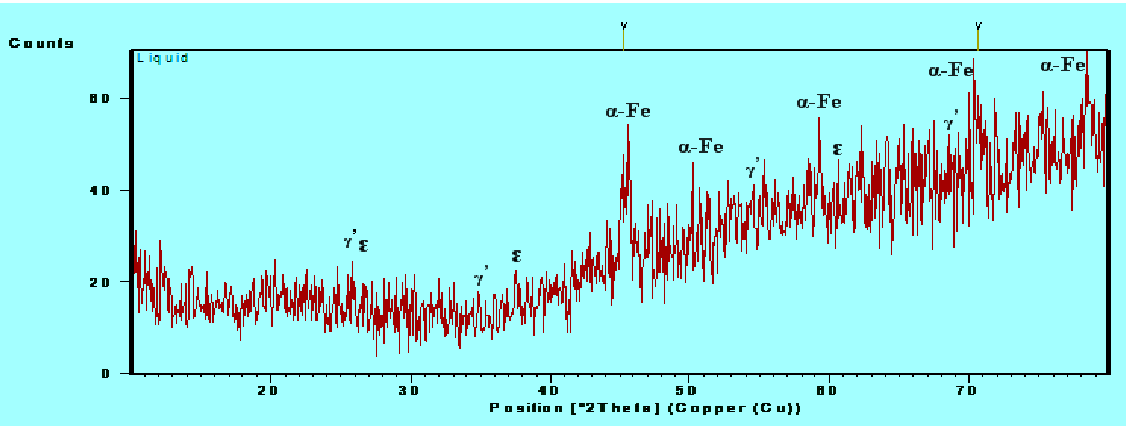
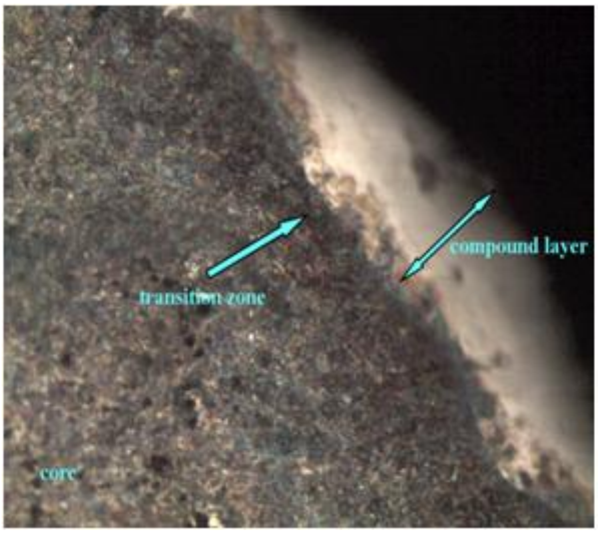



**Fig. 3.1 XRD Pattern of Gas Nitrided medium carbon steel specimen**



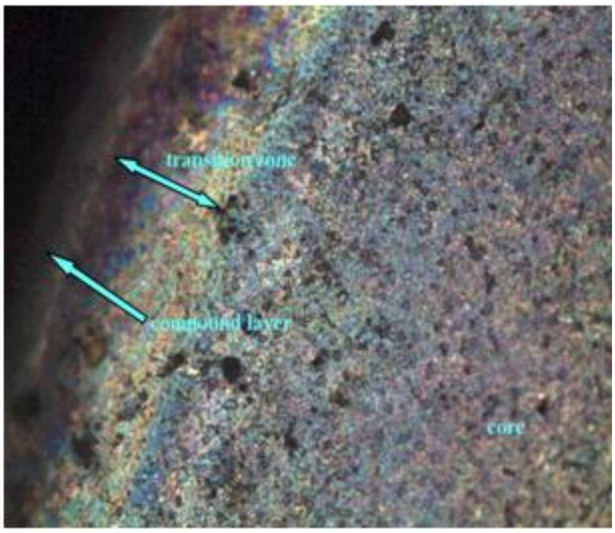




**Fig. 3.3 Optical micro photograph of gas Nitrided** **Fig. 3.4 Optical Micro Photograph of Liquid Nitrided**

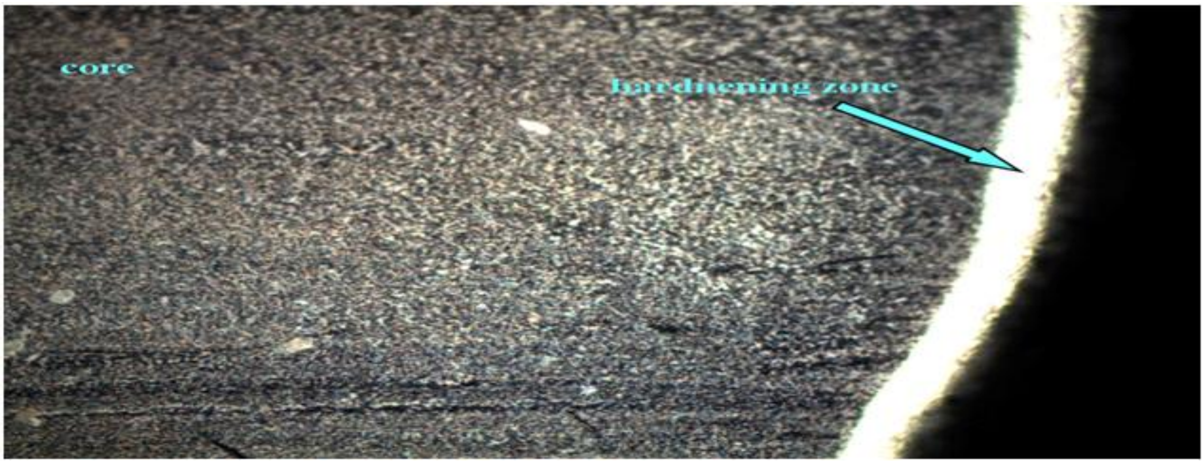



**Fig. 3.5 Optical Photo Micrograph of Induction Hardened Steel Specimen Magnified 20X**

Figure 3.3 is optical micro photograph of gas nitrided medium carbon steel specimen which shows the transition and compound layer similarly figure 3.4 is an observation of the same.. The magnification of the optical micro photograph are in the range of 20X for all the specimen taken into consideration. From the photo micrograph of induction hardened steel have hardening zone is found clearly. And there is no transition zone was presented in the steel.

## IV. CONCLUSION AND FUTURE SCOPE

### 4.1 Outcome of the work

In the present investigation, gas nitriding, liquid nitriding and induction hardening of medium carbon steels were successfully applied. The microstructure, hardness and dry sliding abrasive wear behavior were evaluated. The results obtained are summarized as follows:

Microscopic examinations reveal that the microstructure varies from the surface to core. All components such as compound layer, diffusion zone and core (matrix) are illustrated in the micrographs of gas and liquid nitrided medium carbon steel. Induction hardened steel showed only hardening zone and core. Nitrided steel has a compound layer in the outer surface. Optical microscope examinations show that the layer appears as white layer. X-ray diffraction analysis (XRD) was very useful to determine of the epsilon (ε ) /gamma ($r'$) phases from the XRD patterns of gas nitrided and liquid nitrided steel.

As the distance from surface increases the hardness decreases. The outer surface and diffusion zone have stable nitride phases and this is the reason why the hardness is higher than the tempered martensitic matrix. Induction hardened steel obtained the microhardness (793Hv) which is higher than gas and liquid nitrided medium carbon steel. The wear resistance of the induction hardened steel exhibited lowest wear rate. Wear rate increases with the decrease in the hardness. As comparing with different methods, the induction hardened steel shows the best combination of higher hardness, higher wear resistance with low weight loss and less wear rate.

### 4.2 Optimum results

**Table 4.1 Optimum results of each process and its consolidation**

| **Gas Nitriding Condition** | | **Quenching Condition** | | **Tempering Condition** | | **Micro Hardness** | **Weight loss** | **Wear volume** | **Wear rate** | **Wear resistance** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Temp ($^OC$)** | Soak Time (Hrs) | Temp ($^OC$) from | Medium (78% $N_2$+ other gases) | Temp ($^OC$) | Soak Time (Hrs) | hv | grams | $X10^{-2}$ $CM^3$ | $X 10^{-7}$ $CM^2$ | $X 10^6 CM^{-2}$ |
| **600** | 10 | 600 | Air | 100 | 0.083 | 642 | 0.3246 | 4.13 | 6.88 | 1.453 |
| **Liquid Nitriding Condition** | | Quenching Condition | | Tempering Condition | | Micro Hardness | Weight loss | Wear volume | Wear rate | Wear resistance |
| **600** | 2 | 600 | water | 100 | 0.083 | 566 | 0.4252 | 5.41 | 9.01 | 1.109 |
| **Induction Hardening Condition** | | Quenching Condition | | Tempering Condition | | Micro Hardness | Weight loss | Wear volume | Wear rate | Wear resistance |
| **600** | - | 600 | oil | 100 | 0.083 | 793 | 0.0958 | 1.22 | 2.03 | 4.926 |

The table 4.1 shows that optimum results and its consolidation with respect to three specimens at different temperature ranges. The individual specimen comparison within the treatments has shown the higher temperature range resulting in minimum wear and high hardness. The concerned application with gas and liquid nitriding can use the optimum temperature range mentioned in table 4.1.

The induction hardened specimen has better advantages compared to the other heat treatment process in terms of hardness and wear resistance. Hence induction hardening of the above specification of temperature ranges is suggested for the automotive applications concerned.

**4.3 FUTURE SCOPE**

After studying the Mechanical and wear properties of gas nitrided, liquid nitrided and induction hardened medium carbon steel, the following works are suggested to be carried out in the future:

- Optimization of process parameters can be done to study the relation between process parameters with the results of hardness and layer thickness.
- The similar studies can be made for other types of wear like adhesive wear, Erosive wear and corrosive wear.
- Dry sliding abrasive wear behavior can also be performed by varying its rotational speed, sliding distance and time duration, then by using abrasive grit papers with different grades.

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