EXPERIMENTAL INVESTIGATION INTO THE EFFECT OF AUSTEMPERING ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF HIGH SILICON STEEL (HSS)

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Abstract – *The main objective of this experiment is to observe the effect of Austempering on Mechanical and Microstructural properties of High Silicon Steel (HSS. Steel is the most widely used material in infrastructure, tools, automobiles and machine components because of its high tensile strength and low cost. Hence it is important to understand its behavior and the change in its mechanical properties with prolonged exposure to high temperature environment). The material selected for this experiment was* ***IE EN 45 grade steel****. The material was machined in various dimensions and shapes according to the experimental standards for tensile, hardness and wear testing. Initially, all the experiments were carried out for specimens at room temperature to test mechanical properties under standard atmospheric condition. The specimens were then heat treated i.e. austempered at temperatures of 300ºC and 400ºC, each of which held at 2 and 4 hours and classified into various batches at temperatures of 300ºC and 400ºC, each of which held at 2 and 4 hours and classified into various batches. The tensile test was conducted on The Universal Testing Machine UTM-60 with the hardness test being conducted on the Brinell hardness Tester. The wear experiment was carried on the pin-on-disk wear tester. The wear tests were carried out considering two parameters viz., load and time by keeping one of the parameter constants and varying the other. Surface morphology of the specimens were then studied with the help of Scanning Electron Microscope. The change in mechanical properties and microstructure was compared and studied.*

Key Words: **High Silicon Steel, Austempering, Mechanical properties, Tensile test, Microstructure, Hardness test**.

1. INTRODUCTION

In the modern era, a product is produced by processing of raw materials by various manufacturing methods available. The raw materials available for this process are called as engineering materials. Various engineering materials used today are metal, wood, composite, rubber etc. Metals are most commonly because of their superior properties like tensile strength, hardness, ductility, malleability etc. Desirable properties in a metal can be incorporated by addition of different elements like carbon, boron, silicon etc. One such example is steel.

1.1 Steel

Steel is an alloy of iron and carbon in which the carbon content ranges up to 2 percent. By far the most widely used material for building the world's infrastructure and industry, it is used to fabricate everything from sewing needles to oil tankers. The main reasons for the popularity of steel are the relatively low cost of making, forming, and processing it. The most important alloying component for iron is carbon but other alloying elements i.e. magnesium, chromium, vanadium and tungsten and small amount of sulfur, silicon, phosphorus and oxygen are also present. Mechanical properties like ductility, hardness and tensile strength of steel depend on the amount of alloying materials and their form of presence in iron. The increased carbon content makes the steel harden and strong but less ductile. Understanding such properties is essential to making quality steel.

At room temperature, the most stable form of pure iron is the body-centered cubic (BCC) structure called alpha iron or α-iron. It is a fairly soft metal that can dissolve only a small concentration of carbon. The inclusion of carbon in alpha iron is called ferrite. At 910°C pure iron transforms into a face-centered cubic (FCC) structure, called gamma iron or γ-iron. The inclusion of carbon in gamma iron is called austenite. The more open FCC structure of austenite can dissolve considerably more carbon, as much as 2.1% carbon at 1148 °C, which reflects the upper carbon content of steel, beyond which is cast iron. When carbon moves out of solution with iron it forms a very hard, but brittle material called cementite. The two, ferrite and cementite, precipitate simultaneously producing a layered structure called pearlite, named for its resemblance to mother of pearl. . For steels that have less than 0.8% carbon, ferrite will first form within the grains until the remaining composition rises to 0.8% of carbon, at which point the pearlite structure will form. The above mentioned changes in the microstructure can be observed in this experiment with the help of Scanning Electron Microscope (SEM).

1.2 Effect of Silicon in Steel.

Silicon steel, often called electrical steel, is a steel with silicon added to it. The addition of silicon to steel increases its electrical resistance, improves the ability of magnetic fields to penetrate it, and reduces the steel's hysteresis loss. While the silicon in silicon steel can reduce the rate of corrosion of the iron within it, the primary purpose of adding silicon is to improve the steel's hysteresis loss. The addition of silicon to steel makes the steel more efficient and faster in terms of building and maintaining magnetic fields. Thus, silicon steel improves the efficiency and effectiveness of any device using steel as a magnetic core material.

The percentage of silicon added to silicon steel varies with its intended use up to 6.5%. For some items, such as high-efficiency motors and transformers, silicon comprises approximately 3% of the steel's makeup. In other items requiring less efficiency, such as certain types of motor applications, the amount of silicon can be as low as 2%. Since silicon is used as an deoxidizing agent in the production of steel, it is almost always found in some percentage in all grades of steel.

In our study, high temperature conditions were applied on a highly silicon alloyed steel grades to determine the change in mechanical properties and microstructure after austempering. The change in phase occurring during austempering was observed using the SEM.

2. LITREATURE REVIEW

The literature survey was done on various paper publications. The description of few papers is presented below.

Sharanabasappa. M et al[1], This paper investigates the effect of normal and sliding speed on volumetric property of different combination of phases of hypereutectic steel. The normal load and sliding speed was varied in the experiment and found that wear rate increases with increase of normal load and sliding speed. After the experiment it was found that the sliding speed of 3m/s, volumetric wear is minimum and almost constant for all phases under operational conditions

Jung Moo Lee et al[2], This paper investigates the wear behaviour of Hypereutectoid Aluminium-Silicon alloy A390 using a pin on disc wear machine under dry sliding conditions, by varying the load range and maintaining constant sliding velocity. Two kinds of specimen were selected for the experiments, first one (H2) contained primary silicon particles of size 100μm and the second one (H6) contained silicon particles of size 50 μm in size. After the wear load test, wear loss curves are plotted and they reveal that there exist 3 different wear loss regions irrespective of primary silicon size. Based on the observations from SEM the role of primary silicon particles in the low pressure region, mid load region and high pressure region was suggested.

Naveen Kumar et al[3], studied the dry sliding wear of Lean duplex stainless steel (AISI304) and super duplex stainless steel (AISI310) as a function of heat treatment conditions. The wear test specimens were heat treated at 850°C and followed by oil quenching. These wear tests are carried out using pin on disc technique at Constant -sliding velocity and different sliding distances, constant sliding distance and different sliding velocity and varying load and the weight loss methodology is used to calculate the wear volume. Resulting line diagrams were then plotted and the results were studied.

R.M. Munoz Riofano[4], studied the effect of silicon (Si) on ultrahigh-strength AISI4340 steels in connection with the thermal treatment, as well as the influence of this element on nitriding and, consequently, abrasive wear. Four alloys with different Si contents were nitrided at 350°C (4 and 8 h) and 500^{0}C and 550 °C (2 and 4 h) in a gas mixture of 80 vol% H_2 and 20 vol% N_2. By changing the Si content in the ion-nitriding process, a variety of nitrided layers were produced depending on treatment time and temperature. The increase in Si content in the alloys enhanced their tempering resistance and also improved considerably the hardness of the nitrided layers.

Woo Chang Jeong[5],studied the effect of silicon content and annealing temperature on the formation of retained austenite and the mechanical properties in Fe-0.34% C-1.7% Mn steels. When the silicon content was increased to 1.0 wt% or higher, the amount of retained austenite markedly increased leading to good mechanical properties. The variation in tensile strength-elongation combination had good correlation with that in the amount of retained austenite with both annealing temperature and silicon content.

3. EXPERIMENTAL DETAILS

The materials selected for study is **IE EN 45** based on the literature review. The details of the materials are presented below.

3.1 Material

EN45 is a high silicon steel consisting of 1.75% of silicon composition by weight. It is a manganese spring steel i.e. it is steel with high carbon content, traces of manganese that effect the metal's properties. When used in the oil hardened and tempered condition EN45 offers excellent spring characteristics so it is generally used for springs (such as the suspension springs on old cars).

The chemical compositions and properties of the metal are shown in the following tables

Table 1: Chemical Composition of IE EN 45 Steel

Grade	C (%)	Mn (%)	Si (%)	P (%)	S (%)	Fe (%)
EN 45	0.55	0.75	1.75	0.05	0.05	

Table 2: Material properties of IE EN 45 Steel

Material	EN 45
Density	7.7 g/cc
Tensile strength	850 MPa
Yield strength	310 MPa
Elongation	10%

3.2 Preparation of Specimen

The raw material was machined into various specimens for different test by following the experimental standards. Specimen for wear test of size Ø10x30 mm were prepared as per ASTM G99. A 30mm thick cylindrical work piece was prepared to carry out the hardness test. As per the standard length requirement the material was cut using lathe. Two sets of specimens were made with each set containing four specimens

3.3 Austempering

One set of specimens consisting of four pieces were heated to temperature of 900^0C. The temperature of the furnace was then reduced and maintained at 400^0C for 2 hours after which two pieces were removed and cooled to room temperature. Remaining two pieces were kept at the same temperature for 2 more hours. Another similar set of specimens was made and heated to temperature of 900^0C and reduced to 300^0C for 2 hours for two specimens and 4 hours for the remaining two specimens.

Fig 1- Austempering of Specimen

3.3 Tensile Test

Tensile test was conducted on Universal Testing Machine (UTM-60) as shown in Figure 2 to determine the ultimate tensile strength, breaking strength, maximum elongation and reduction in area. From these measurements the following properties were determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics. The specimen was machined to match the experimental standard for tensile testing. Initially, all the dimensions of the specimen were noted .The specimen was then gripped vertically and firmly in the jaws of the UTM with a calibrated extensometer attached to it. The load was gradually applied at increments of 500 kg each time and the corresponding extensometer reading was noted. This was continued till the yield point was reached which was determined by the extensometer showing higher values. The load at the yield point was recorded along with the maximum load and the breaking load. The broken pieces were put together and the final length L_f and the final diameter at the neck are noted. Percentage elongation, percentage reduction in arm, modulus of elasticity and modulus of toughness were calculated from the data obtained.

Fig 2- Universal Testing Machine (UTM-60) used for the experiment

3.4 Hardness Test

Hardness test was conducted on Brinell hardness testing machine to determine the HBN of the specimens. The required load F and the diameter of the ball D were set on the machine. The specimen was placed on anvil so that its surface will be normal to the direction of the applied load. The specimen was gradually brought in contact with the indenter and the load was applied for about 15 seconds. The specimen was then taken out from the machine and indentation was measured using microscope. Brinell hardness number was then determined as shown in the following section.

Fig 3- Brinell Harndness Testing Machine used for the experiment

3.5 Dry Sliding Wear test

Wear test was carried out on the Pin-on-disc type wear testing machine as shown in Fig. The test specimen was clamped in jaw. Wear track diameter was fixed at 60 mm. The tests were conducted for specimens from all the five batches in three different loading conditions. The rotational speed of disc was fixed at 800 rpm. The loads were varied from 2kg to 6kg in steps of 2 kg and each load was applied for a period of 60 minutes. The readings were taken from the digital display. From the data recorded, wear versus time graphs were plotted to study and compare the change in wear rate

Fig 4- Pin on disc wear testing machine setup

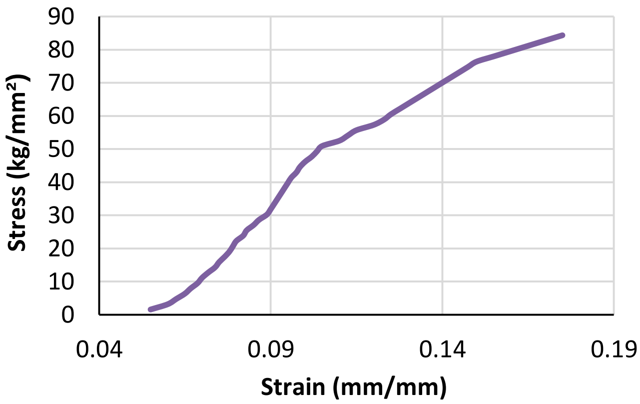
4. RESULT AND DISCUSSION

4.1 Tensile Testing

1. Diameter of the specimen, d_0= 20 mm
   d_f= 19.8 mm
2. C/Sn area of the specimen, A_0= 314.15 mm^2
   A_f= 307.9 mm^2
3. Gauge Length, L_0= 200 mm
   L_f =207 mm
4. Load at yield point, F_y= 9500 kg
5. Ultimate Load, F_{max}= 26500kg
6. Breaking Load, F_b= 25500 kg

Table 3- Results of Tensile Test

Sl. No.	Load	Deformation	Stress	Strain
	F	ΔL	σ	ϵ
	kg	mm	kg/mm^2	-
1	500	1	1.591343	0.055
2	1000	2	3.182686	0.06
3	2000	3	6.365372	0.065
4	4000	4	12.73074	0.0718
5	6000	5	19.09612	0.078
6	8000	6	25.46149	0.083
7	10000	8	31.82686	0.09
8	12000	8	38.19223	0.094
9	14000	9	44.55761	0.0985
10	16000	11	50.92298	0.105
11	18000	14	57.28835	0.12
12	20000	16	63.65372	0.13
13	22000	18	70.0191	0.14
14	24000	20	76.38447	0.15
15	26000	24	82.74984	0.17
16	26500	25	84.34118	0.175



Graph 1- Stress-strain graph

The above graph resembles the stress-strain curve of cast iron rather than mid steel. This is because of the high carbon content present in the specimen which increases the hardness of the material and makes it more brittle.

4.2 Hardness Test

Specimen thickness= 30 mm
Diameter of indenter= 2.5 mm

Table 4- Hardness test results

Batch	Load	Time of load application	Diameter of indentation	Brinell Hardness number
	F	T	d	HBN
	kgf	sec	mm	kgf/mm
Non Austempered	187.5	15	1.1	**187.23**
400°C at 2 hours	187.5	15	1.3	**130.96**
400°C at 4 hours	187.5	15	1.5	**95.94**
300°C at 2 hours	187.5	15	1.2	**155.61**
300°C at 4 hours	187.5	15	1.4	**111.35**

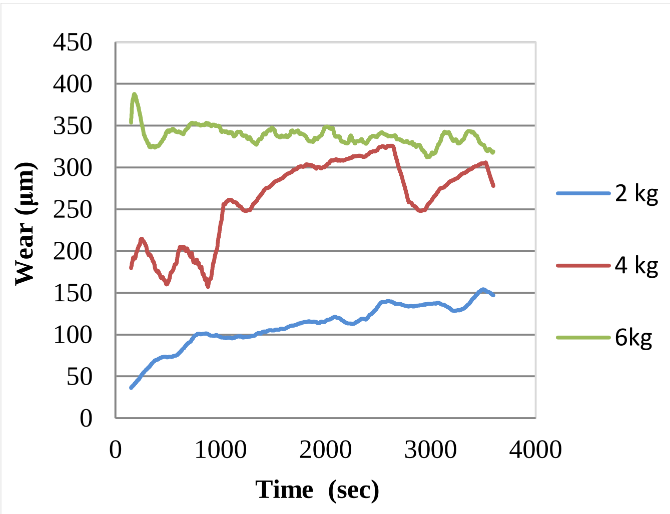
The HBN of the specimens from different batches were calculated with the following

$$BHN = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

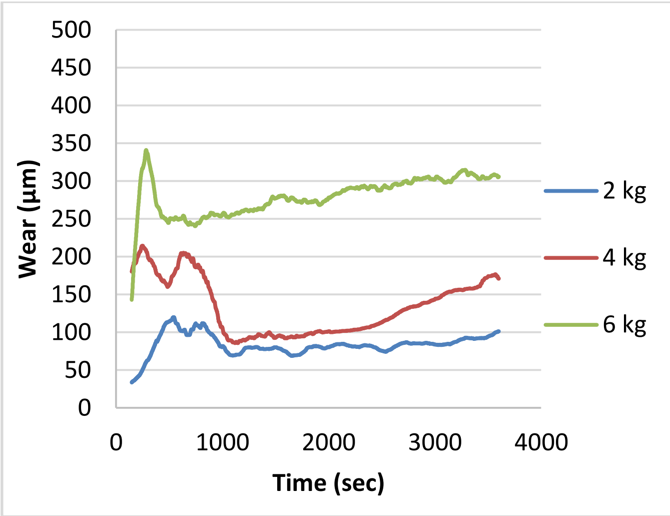
Brinell hardness number was the highest for the non austempered specimen at room temperature and was found to decrease in austempered specimens with longer holding times.

4.3 Wear Test

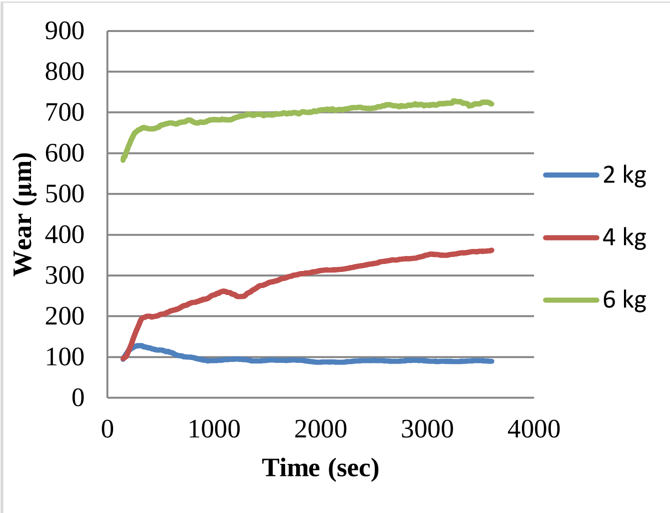
The graph of Wear vs. Time was plotted from the data obtained from the wear test of austempered and non austempered conditions



Graph 2- Wear Behavior of Non Austempered Specimen



Graph 3- Wear Behavior for Austempered Specimen at 300ºC for 2 hours



Graph 4- Wear Behavior for Austempered Specimen at 300ºC for 4 hours

Graph 2 indicates the wear behavior of a non austempered specimen at room temperature. It evident that wear rate increases with increase in load applied. From Graph 3, we observe that the pattern of change in wear rate for specimens is similar with the 6 kg specimen showing maximum wear of around 350 µm. However, the wear rate is found to double for the same load in the specimen austempered at 300ºC for 4 hours as seen in Graph 4. In general, the wear rate of the specimen is increasing with increase in holding time which indicates that the wear resistance of the material decreases with longer holding times.

4.4 Microstructure

The microstructure of all the specimens was observed under Scanning Electron Microscope and the images obtained were studied

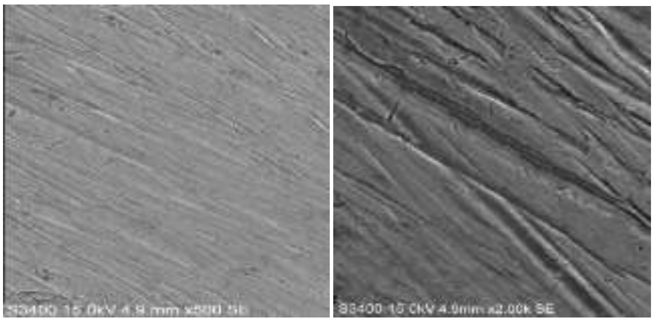


Fig 5- x500 and x2k magnified SEM image of Non-austempered specimen

Since the specimen is at room temperature there are no effects of heat treatment seen. The diagonal ridges and lines as seen in X2000 magnification.

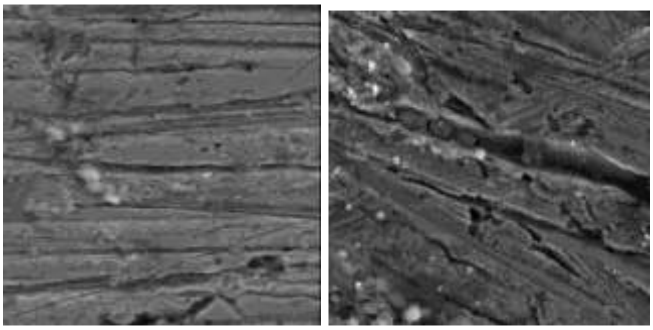


Fig6- x2k and 2.5k SEM images of specimen austempered at 300ºC for 2 hours and 4 hours respectively

A significant change from the non austempered specimen is observed. Effects of heat treatment are seen with more cracks appearing in specimen with longer holding time. Slight carbide precipitation (Reaction of Carbon with oxygen in the atmosphere at higher temperature) is also clearly seen as white deposits at some locations.

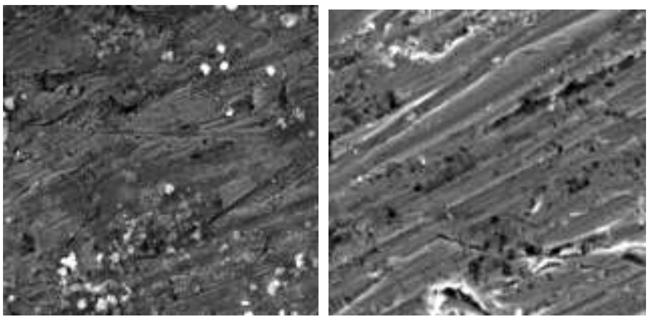


Fig7- x2k and 2.5k SEM images of specimen austempered at 400ºC for 2 hours and 4 hours respectively

The gray area represents pearlite while the white area represents the ferritic phase present in the matrix. Due to the presence of varying amount of pearlite and ferrite, the matrix is having a non-homogeneous structure. A lot of black spots are seen on the surface of the specimen as carbon deposits in the form of graphite.

5. Conclusion

Tensile, hardness and wear behavior of the IE EN 45 high silicon steel specimen were studied and compared between room temperature and austempered at various temperatures for different holding conditions.

5.1 Tensile Test

The stress strain curve obtained from tensile test revealed that the hardness of material is high due to presence of high amount of carbon content. This was later confirmed from the Brinell hardness test carried out on non austempered.

5.2 Hardness Test

Hardness was found to be maximum in non austempered specimen and tends to decrease with increase in holding times for austempered specimens. This indicates that the material gets softer with longer exposure to high temperature environment

5.3 Wear Test

A Similar change in wear rate was observed with austempered specimens. The maximum wear rate was found to double with increase in holding time from 2 hours to 4 hours.

5.4 Microstructure

Microstructure was found to be smooth and homogenous for non austempered specimen. In austempered specimens cracks and depositions were observed which were results of heat treatment. The surface analysis of the specimen was done under SEM which showed that Bainite, and Pearlite structures were produced by austempering of the specimen. At lower austempering temperature the nucleation of bainite is faster, but during the formation of bainite, the rejected carbon diffuses only to the shorter distance and thus formation of fine bainite and austenite takes place. Pearlite is found to have formed in specimen which was austempered at high temperature with longer holding times.

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