Fatigue Behavior Analysis of Differently Heat Treated EN9 Steel

[1]Asha Kumari, [2]Pradeep Kumar, [3]Alok Bihari Singh

[1]Research Scholar, [2]Assistant Professor, [3]Assistant Professor
[1]Department of Mechanical Engineering,
[1]Yagyavalkya Institute of Technology, Jaipur, India.

Abstract : The utility and applicability of medium carbon steel for engineering applications is very precisely and widely popular these days. There are so many engineering applications of this material including shaft manufacturing in different fields of industries. It was also observed that the reason behind approximately 90 percent of the failure is fatigue. So it is very important and prestigious work to study the different reasons, behavior and aspects of fatigue failure so that the best possible life of a given specimen, types of fracture and its features can be studied. The material selected for this current investigation is EN9 which contains 0.52% carbon. It is selected because of its wide applicability in engineering application especially in shaft application. Further it is subjected to different heat treatment processes at different temperatures and for different time period. The microstructure analysis has done before and after heat treatment. The endurance limit was also determined for all the cases.

Index Terms **- Medium Carbon Steel, Fatigue failure, EN9 Steel, Heat Treatment, Endurance Limit.**

1. INTRODUCTION

It was observed by many scientists or researchers that a material will fail at a much lower stress while subjected to cyclic loading than that of static loading. And the term “fatigue” was used by the scientists for the failure under cyclic or dynamic loading. It was also observed that the reason behind approximately 90 percent of the failure is fatigue [1]. So it is very important work to study the different reasons, behavior and aspects of fatigue failure so that we could suggest the best possible life of a given specimen, types of fracture and its features and also suggest some applicable methods to prevent fatigue before time.

In current work it is to predict and determine the dependency of fatigue life on different heat treatments. The material selected for this current investigation is EN9 which contains 0.52% carbon. The same material was subjected to different heat treatment processes like annealing, normalizing, quenching and tempering at different temperatures and for different time period. The endurance limit was also determined for all the cases. Endurance limit is defined as the stress point below which there is no possibility of fatigue failure despite of application of innumerable number of cycles [2]. The generated effect on microstructure and other mechanical properties was also studied. The focus was also towards the study of relation between fatigue strength and microstructure. The microstructure analysis has done by scanning electron microscope and optical microscope. The later work is to correlate the fractographic study of microstructure and fatigue strength.

Researchers had presented the established relationship between mechanical properties and observed structure of steel after heat treatment. They had investigated the relationship between the fatigue limit and mechanical properties of medium carbon steel. The microstructures obtained and mechanical properties such as tensile properties, hardness and fatigue resistance were investigated after subjecting them to heat treatment or prestraining. The effect of tempering on the mechanical properties and microstructure of medium carbon bainitic steel through optical microscopy, electron back-scattered diffraction, TEM and XRD were analyzed. And results obtained were showing that the sample tempered at intermediate temperature (Around 300°C) occupied the optimal balance of strength and toughness by maintaining a certain level of plasticity. The microstructure of the steel was not sensitive to such tempering temperatures. The temperature was increased beyond this limit to 450°C, the formation of significantly coarsened bainitic ferrite plate and the occurrence of a small quantity of carbide precipitation presents with low toughness. The amount of retained austenite increases with the tempering temperature before 400ºC, followed by decreasing with further increase in the temperature. This behaviour was related to the competition between retained austenite further transforming into bainite and decomposing into carbide during tempering [3].

In last 20 years, there have been major advances in the field of production of steel. Steel is the most important alloy which is used as a structural material and this work will show some technological advances in steel heat treatment. The micro-structures of most steels are well known for their effects on mechanical properties under different heat treatment conditions. For instance, both martensite (obtained during rapid cooling) and pearlite (obtained during slow cooling) comes from austenite.

2. EFFECT OF RESIDUAL ELEMENTS ON STEEL

Some Residual elements like phosphorus, silicon and Sulphur were found undesirable due to their disadvantages. The change in ductility and toughness is due to the presence of phosphorus. When the plane carbon steel is subjected to heat treatments it has tendency to form brittle compound of iron. The presence of phosphorus results in ductility decrement. Silicon is considered as less harmful to steel but it is also imposing some negative impact on steel like poor surface quality because of silicon has a tendency to combine with others [4].

It can be concluded from the above that the residual elements are mainly not beneficial to steel but still they can import some good properties if they are present in steel with some amount. Roughness and hardness may be improved with appropriate presence of manganese and silicon. The reason behind this improvement is that they can dissolve in austenite and cause a significant decrease in the transformation rate of the austenite phase to pearlite or upper bainite.

The strength and hardness will increase with the presence of carbon content but its higher quantity will results in ductility. It results in de-oxidation of molten metal by forming silicon dioxide. It also results in increased cast ability. Manganese neutralizes the bad effects of Sulphur which results in increased hardness and strength. Phosphorus increases the hardness and strength when dissolved in ferrite but if present with larger quantity, reduces the ductility. Sulphur reduces the iron carbide formation ability. It lowers toughness but imparts brittleness to chips removed in machining operation [5]. The primary function of adding carbon content is to increase strength with ductility decrement.

3. Medium Carbon Steel

This is the most widely used steel for commercial and industrial use. It contains carbon content in between 0.3% - 0.8%. Medium carbon steels are economic and best suited for required mechanical properties such as high strength and toughness. It is applicable for the large variety of engineering applications. There are some certain advantages of using medium carbon steel as it has 60%-70% machinability so cut slightly better than low carbon steel. It has good toughness and ductility and has enough carbon to be quenched to form martensite and bainite. It is found a good balance of properties in form of strength and hardness. It is extremely popular for its different applications. It has good formability also. There are some disadvantages of medium carbon steel as its hardenability is low, the loss of strength and embrittlement decreased at low and high temperatures. It is corrosive in most environments. But still its uses and applications are very large.

4. Fatigue of Steel

It was observed since 1830 that a metal fails under the application of repetitive or fluctuating stress is much lower than that required to cause fracture on a single application of load. Fatigue failures are failures occurring under conditions of dynamic loading because it is observed that these failures occur only after a considerable period of service. Fatigue can be seen in automobiles, aircraft, turbines, etc. subject to repeated loading and vibration. It was also observed that the reason behind approximately 90 percent of the failure is fatigue. Here the objective is to study the effects of fatigue on mechanical and physical properties associated with the heat treatment and the most common techniques used in it.

4.1 Fundamentals of Fatigue

Fatigue comes into account anytime with result in brittle appearing fracture with no gross deformation at the fracture, where fracture surface is normal to the direction of the principal tensile stress.

(a) (b)

Fig. 1. (a) Ductile and (b) Brittle Fracture in Steel [6]

For fatigue failure three basic factors are mainly responsible these are as below:

a) A maximum tensile stress of sufficiently high value.
b) Large variation or fluctuation in applied stress.
c) A sufficiently high cycle for the applied stress.

4.2 Stress Cycles

Fatigue failures are result of fluctuating stresses. Figure 2, Figure 3 and Figure 4 shows some of the fluctuating stress cycles.

a) **Completely reversed cycle of stress of sinusoidal form:** In this case of stress cycle, maximum (σmax) and minimum (σ_{min}) stresses are opposite in sign and equal in magnitude. This cycle is obtained in a rotating shaft operating at a constant speed.
b) **Repeated stresses cycle:** The maximum and minimum cycles are not same as shown in this stress cycle graph.

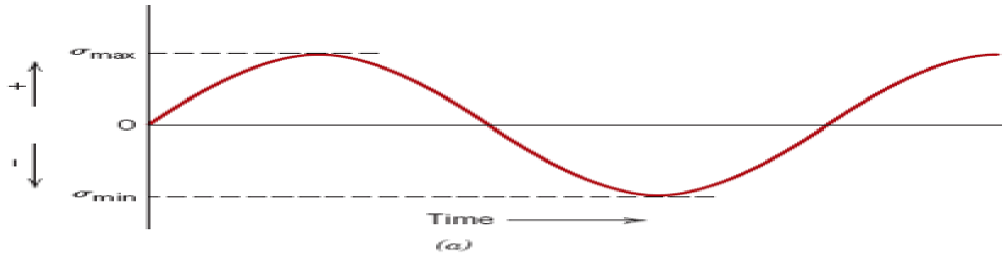

Fig. 2. Completely Reversed Stress Cycles

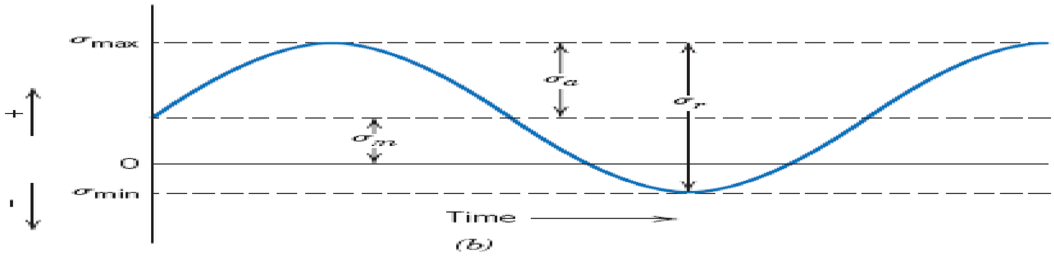

Fig. 3. Repeated Stress Cycles

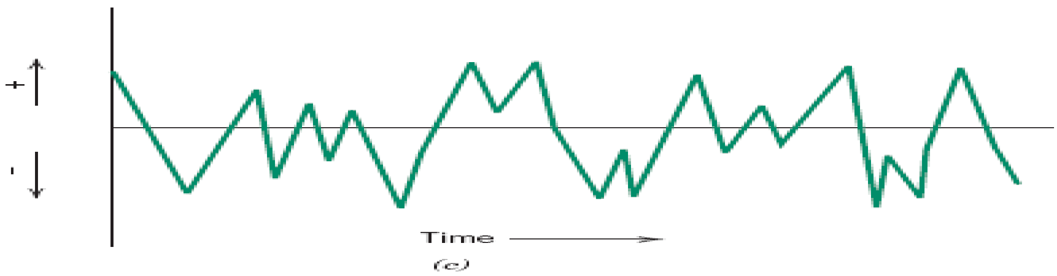

Fig. 4. Random Stress Cycles

c) **Irregular or random stress cycle:** It is obtained due to periodic unpredictable overloads and complicated cycle in nature.

5. SPECIMEN SPECIFICATION: The first work of this project is specimen preparation. The specimen prepared should be compatible to the machine we are working with. The specimen we got from steel trader is of EN9 type and was in cylindrical form. The current steel grade consists 0.50 % – 0.60 % carbon composition and comes under the category of medium carbon steel. It is medium carbon steel with combination of pearlitic and ferritic mixture. So it has required amount of hardness and strength as well as moderate ductility.

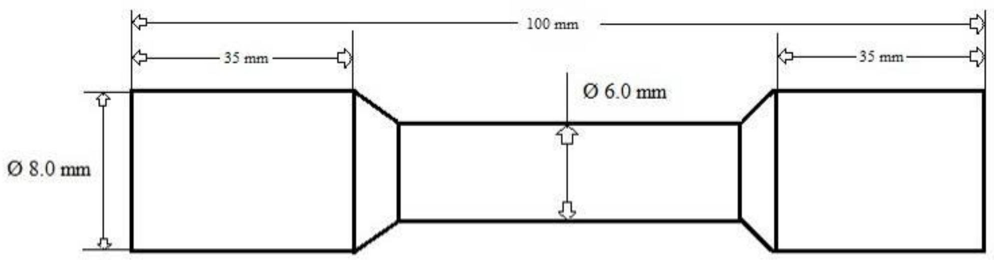

Fig. 5. Specimen used for Tensile Test and Fatigue Test

6. RESULTS AND ANALYSIS:

6.1 INTRODUCTION

The material selected for the current research work is EN 9(Enriched nicrome steel 9) or SAE 1050 or AISI – C 1050. The objective in the present work was to determine the various mechanical properties like yield strength, ultimate tensile strength and ductility or percentage of elongation and efforts have made to establish the relationship between structure and property. This was accountable with the reason that the microstructure of steel was greatly influenced by different heat treatment processes [7]. Lastly the fatigue behavior analysis need to be study with respect to different heat treatment processes followed by fatigue life estimation and the limit of fatigue for all different heat treated specimens.

6.2 MICROSTRUCTURAL RESULTS AND ANALYSIS

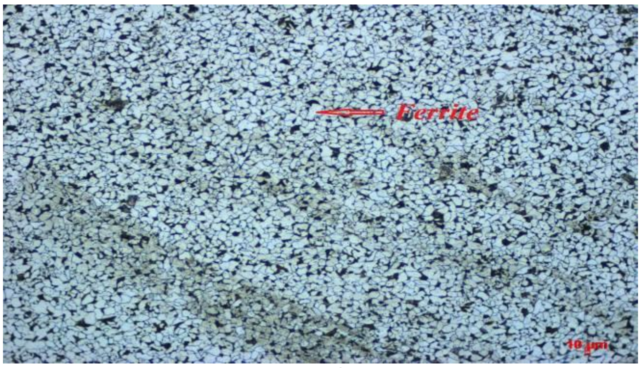

Fig. 6.1. Optical Micrograph of Normalized Steel

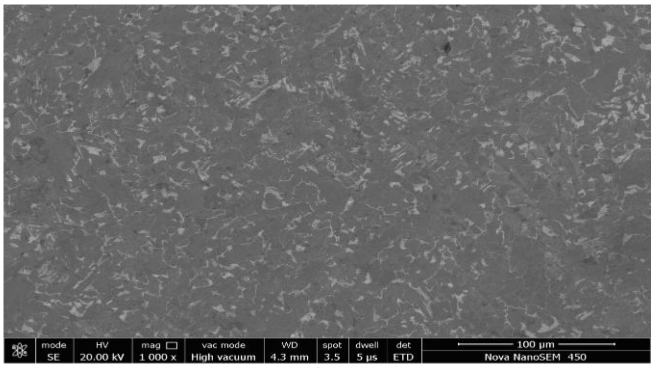

Fig. 6.2. SEM Micrograph of Normalized Sample at 1000X

During microstructure analysis and investigation of EN9 normalized steel it was found the grains are uniaxed and the grain boundaries was not clearly visible. Below is the picture of typical optical micrograph of normalized EN9 steel.

The microstructure of normalized EN9 steel contains ferrite (light areas) and pearlite (dark areas) and a typical micrograph were taken with the help of scanning electron microscope in different magnifications contains of ferrite and pearlite, which is free from carbides. The next fractograph is for the annealed samples and it shows the microstructure changes come in to account due to annealing heat treatment. This fractograph shows in the microstructure of annealed sample that it comprises of both ferrite and pearlite structure in equal proportion as like previously shown normalized ones and grain boundaries are also not well defined too. The magnification of fractograph showing in figure 6.2 and figure 6.4 is 1000X and the same for figure 6.3 and figure 6.5 is 10000X.

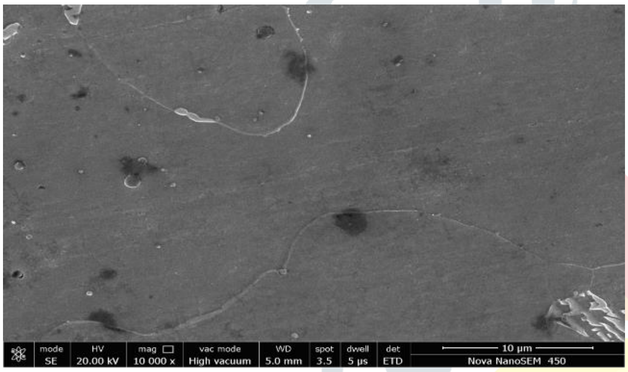

Fig. 6.3. SEM Micrograph of Normalized Sample at 10000X

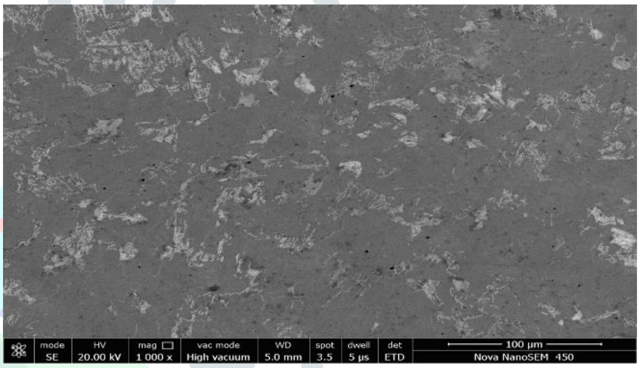

Fig. 6.4. SEM Micrograph of Annealed Sample at 1000X

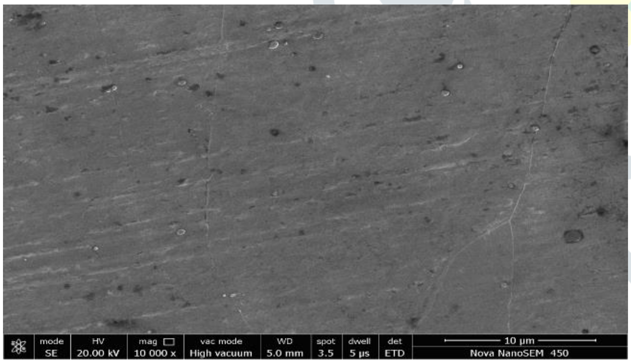

Fig. 6.5. Annealed Sample at 10000X

Fig. 6.6. Tempered Sample at 250^0C for an Hour at 10X

As shown in pictures the SEM micrograph of annealed sample at 1000X and 10000X magnification are showing grain boundaries coarser than of normalized one. Below shown pictures are some other micrographs which is giving a clear view about the microstructure change at different working tempering temperatures. One noticeable thing is that, here we can identify the formation of Spherodized carbide increases as the tempering temperature increases.

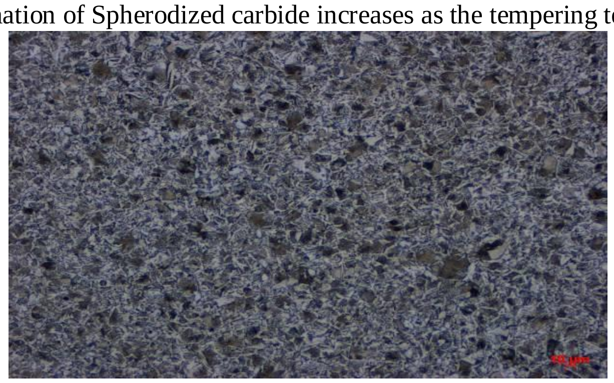

Fig. 6.7. Tempered Sample at 250^0C for an Hour at 20X

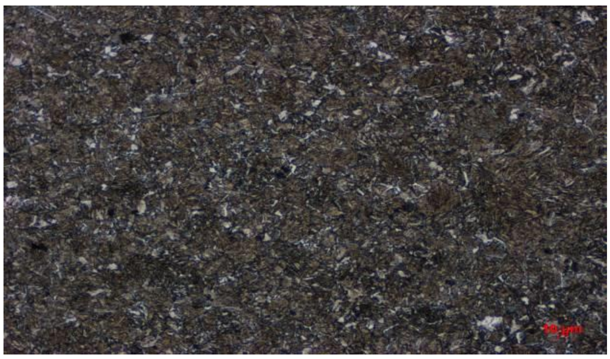

Fig. 6.8. Tempered Sample at 450^0C for an Hour at 20X

Fig. 6.9. Tempered Sample at 450^{0}C for an Hour at 10X

Fig. 6.10. Tempered Sample at 650^{0}C for an Hour at 10X

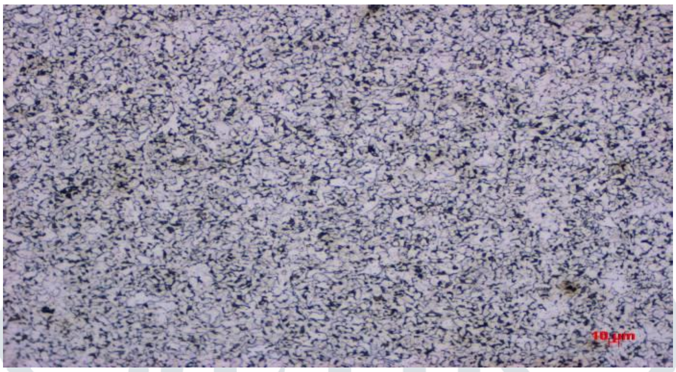

Fig. 6.11. Tempered Sample at 650^{0}C for an Hour at 20X

The above shown pictures are optical micrograph of tempered samples at different temperatures and different magnifications. It can be identified easily the differences between the microstructure of these micrographs. All optical micrographs were taken in 10X to 20X magnification range. Here it can be observed easily that the formation of ferrite decreases from 650^{0}C to 250^{0}C, particularly in case of low temperature tempering i.e at 250^{0}C, tempered martensite were formed due to rapid cooling and cementite formation decreases gradually. It was also observed that in case of intermediate tempering i.e. at 450^{0}C both cementite and martensite were formed. In case of high temperature tempering (650^{0}C) much more cementite and martensite were formed which may increase more softness as comparison with low temperature tempering.
As per the obtained results of several researchers the heat treatments of a given sample results in improved or altered mechanical and physical properties and the change in micro structure due to heat treatment plays a major role for the same. It is well known fact that the mechanical properties depends on microstructural changes, so tensile test performed on several heat treated specimens to observe the change in properties of differently heat treated specimens.

7. Rockwell Hardness Testing and Analysis of Hardness Measurement

Rockwell hardness tester is the most widely used hardness tester and generally accepted due to its speed, Freedom from personal error, Ability to distinguish small hardness difference and Small size of indentation. The hardness is measured according to the depth of indentation, under a constant load. By the help of Rockwell hardness tester it can be obtained the hardness value for as received and also for differently heat treated specimens. The obtained values of hardness are shown in table drawn below and by the help of which it is easy to draw some comparison graphs of hardness for as received condition and hardness of differently heat treated specimen.

Table 1
Variation of Hardness for Heat Treated Specimen

Specimen Specification	Time in hours	Hardness (Rockwell HRC)
As Received	Nil	13
Normalized at 850^{0}C	1 Hour	25
Annealed at 800^{0}C	1 Hour	09
Tempered at 250^{0}C	1 Hour	48
	2 Hour	42
Tempered at 450^{0}C	1 Hour	44
	2 Hour	39
Tempered at 650^{0}C	1 Hour	41
	2 Hour	36

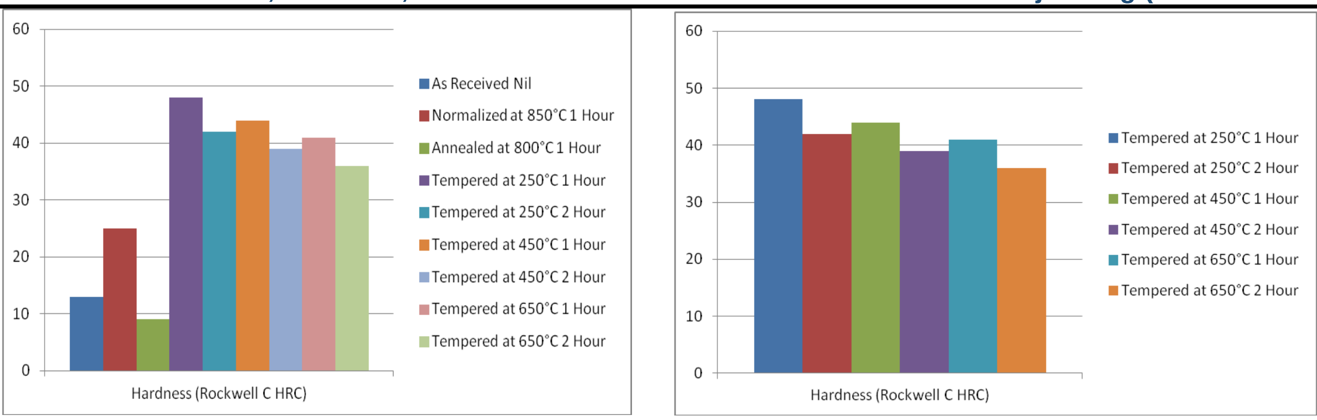

Fig. 7. Comparison Graph of Hardness

7.2.1 Result after Annealing: The value of hardness for annealed specimen is 9 HRC or 55 HRA. Here it is showing the value of hardness in terms of HRA Scale because after annealing the specimen becomes soft and its harness value falls below 20 HRC. So HRC scale was not giving accurate value and the obtained value was not valid too.

7.2.2 Result after Normalizing: The value of hardness was found 25 HRC after normalizing. It results in more hardness than annealed specimen. The reason behind this is formation of pearlite is more than ferrite after annealing.

7.2.3 Result after Hardening and Tempering: It is found that hardening and tempering of the specimen at 250°C for an hour is giving the value of hardness as 48 HRC and when the tempering time is extended to two hours the hardness is 42 HRC. When the hardening and tempering of the specimen has performed at 450°C for an hour the hardness was 44 HRC and after extending the tempering time to two hours it is 39 HRC. It is 41 HRC and 36 HRC when tempered at 650°C for one and two hours respectively.

7.2.4 Comparison: The specimen becomes softer after annealing then untreated condition hardness value. The value of hardness increased after normalizing and after hardening and tempering the specimen was hardest then other all previously processed specimens due to formation of fine tempered martensite.

8. Tensile Test Results and Analysis

Table 2

Tensile Properties Variation of differently Heat Treated specimens

Specimen Specification	Time in hours	Yield Stress (YS) in MPa	Ultimate Tensile Stress in MPa	% of Elongation	Maximum Load in KN
Specimen as Received	Nil	397.61	583.16	21.60	45.795
Normalizing at 850^{0}C	1 hour	433.627	716.08	17	56.24
Annealing at 800^{0}C	1hour	425	707	18.5	55.57
Quenched from800^{0}C and Tempered at 250^{0}C	1hour	819	978	11	76.802
	2 hours	728	951.69	18	74.736
Quenched from 800^{0}C and Tempered at 450^{0}C	1hour	619	934	22.5	73.347
	2 hours	465	762	24	59.839
Quenched from 800^{0}C and Tempered at 650^{0}C	1hour	741.12	891	24	69.970
	2 hours	618.51	783	26	60.625

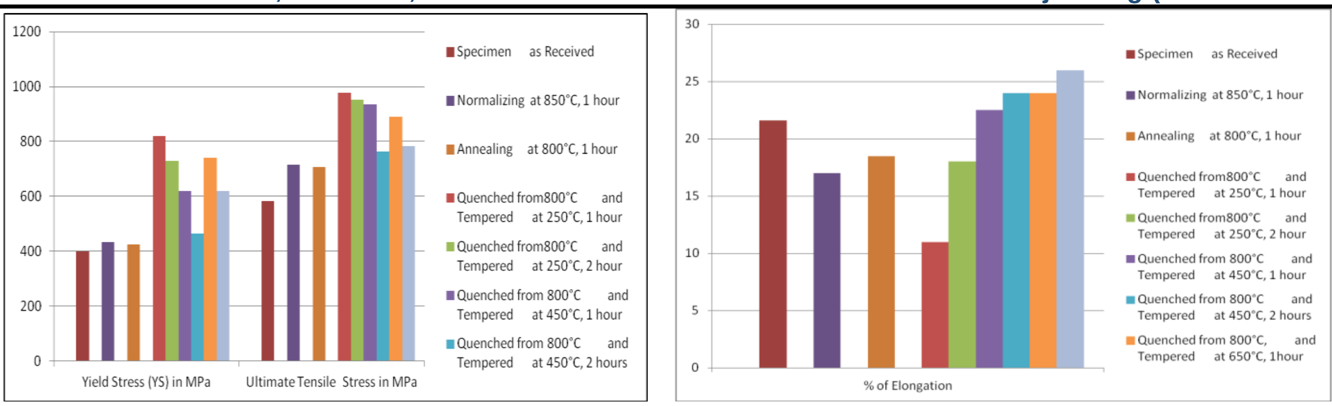

Fig. 8. Comparison Graph of Yield Stress and Ultimate Tensile Stress and Ductility

9. Fatigue Life Estimation Results and Analysis

The fatigue test is performed on Fatigue testing machine which gives the data in form of results, which is showing the variation of life cycle with respect to induced stress. All the dimensional values are considered as per the predefined dimension of the specimen which is shown in table 3 below. The notation N represents the number of cycles to failure and yield stress is expressed in terms of MPa. To know the fatigue mechanism, nicrostructural testing has been performed after fatigue testing.

Table 3

Value of log N for differently heat treated steel

Sample Name	Yield Stress (YS) in MPa	No. of cycles to failure (N)	Value of Log N
Normalizing at 850^0C	433	1.6×10^5	5.2
Annealing at 800^0C	425	3.2×10^5	5.5
Quenched from 800^0C and Tempered at 250^0C, 1 hour	819	4.9×10^4	4.9
Quenched from 800^0C and Tempered at 250^0C, 2 hour	728	1.9×10^5	5.3
Quenched from 800^0C and Tempered at 450^0C, 1 hour	619	2.51×10^5	5.4
Quenched from 800^0C and Tempered at 450^0C, 2 hour	465	3.98×10^5	5.6
Quenched from 800^0C and Tempered at 650^0C, 1 hour	741	1.25×10^5	5.1
Quenched from 800^0C and Tempered at 650^0C, 2 hour	618	3.98×10^5	5.6

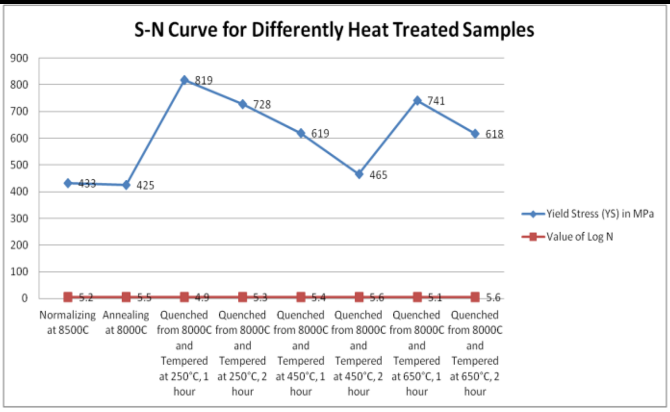

Fig. 9. S-N Curve for Differently Heat Treated Samples and comparison of values of Log N

9.1 Fractograph after Fatigue Failure

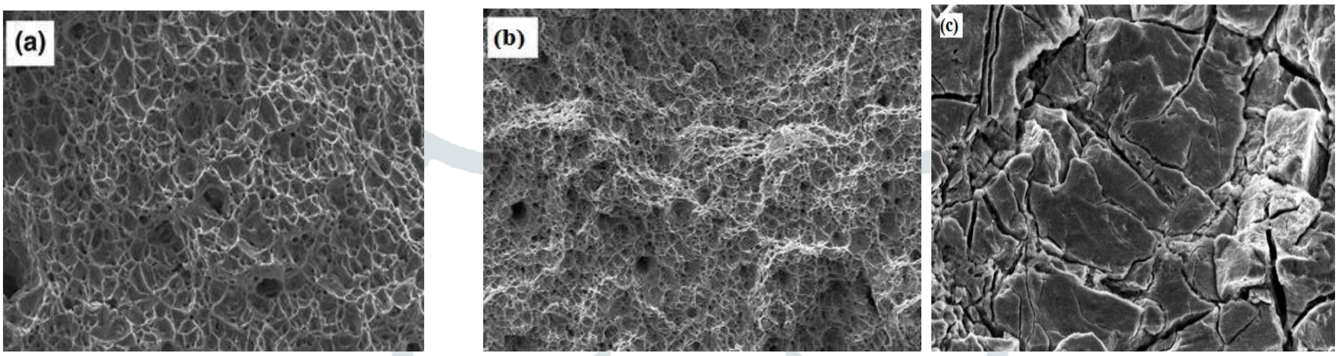

Fig. 10. (a), (b) and (c), Fractograph after Fatigue Testing

10. Conclusions:

The surface of several specimens was investigated with help of scanning electron microscope to find non-propagating cracks. While studying the fracture surfaces the assumptions of observed endurance limit is correlated to a non propagating condition of cracks. It is clearly visible from tensile test fractographs that there are dimple like structures are also present which indicates the materials nature is still ductile, Where some dimple structures are obtained in the post tensile fractographs with nested loops.

Fatigue life estimation by fatigue testing machine is based upon the yield strength of the specimen [8]. The application of different loads and the fatigue limit determined is tabulated in the above shown table and showing different fatigue limit for differently heat treated specimens. From the results obtained following conclusions are drawn:

If tensile strength increases it will results in increased endurance limit. It has been calculated as 573 MPa for low temperature tempering i.e. tempering at 250°C. As tensile strength started decreasing with tempering time, it will also results in endurance limit decrements. It was observed that the endurance limit for normalized steel specimen is higher than annealed steel specimens at a particular stress level (above the endurance limit 346 MPa) the number of cycles required to cause fatigue failure is less for normalized steel. It is observed in case of tempered specimens at different tempering temperature at a particular temperature there is decrement in endurance limit with increment in tempering time. It is highest for 250°C at one hours i.e. 573 MPa and lowest for 250°C at two hours which is 473 MPa.

It is found the same variation in endurance limit for the rest tempering temperatures and was observed that we are getting stabilized effect at 250°C for time more than one hour and the same effect was observed at high tempering temperature i.e. at 650°C for one hour. It was also observed that beyond one hour tempering time the effect of time has no practical significance on endurance limit. It was found that the effect of time is more significant at intermediate temperatures as there is a sharp fall in endurance limit found beyond one hour tempering time.

It was also concluded that the microstructure change has a big impact on fatigue properties. It can be seen clearly that the grain size defers with the time of heat treatment and temperature. It was found finer grains in case of normalizing (ferrite and pearlite) in comparison with annealing. Carbide formation takes place in case of tempering with some ferrite structure. And it includes both strength and ductility which helps to alter the fatigue properties.

REFERENCES

[1]. Lakhtin Y.M., Engineering Physical Metallurgy and Heat Treatment. Mir Publ., 1977.

[2]. Oberg, E., Machinery's Handbook, 25th ed., Industrial Press Inc., 1996.

[3]. Smith, W.F. and Hashemi, J., Foundations of Materials Science and Engineering, 4th ed.,McGraw's - Hill Book, 2006.

[4]. Avner, S.H., Physical Metallurgy McGraw Hills, 2nd ed., 2008.

[5]. Singh V., for standard publisher's distributors, Delhi, 2008, pp.417.

[6]. A. Sabet Ghorabaei, S.S. Ghasemi Banadkouki, "Abnormal mechanical behavior of a medium-carbon steel under strong ferrite-pearlite-martensite triple-phase microstructures" Materials Science & Engineering A, June 13, 2017

[7]. Sung Hyuk Park, Chong Soo Lee, "Relationship between mechanical properties and high-cycle fatigue strength of medium-carbon steels" Materials Science & Engineering A, February 21, 2017

[8]. J. Kang, F.C. Zhang, X.W. Yang, B. Lv, K.M. Wu, "Effect of tempering on the microstructure and mechanical properties of a medium carbon bainitic steel" Materials Science & Engineering A, 17 January 2017.

[9]. Hua Zhang, Yan-xin Wu, Jian-xun Fu, Jie Xu, Qi-jie Zhai, "Influence of On-Line Tempering parameters on microstructure of medium carbon steel" Journal of Iron and Steel Research, International, Januart 15, 2017

[10]. Suresh Chand, Madhusudan D, K. Premalatha, Ayesha Fatima, Shaik Shakila, "Study of effect of phases on Charpy Impact Energy of Steels" International Journel of Material Science, Volume 11, November 1,2016