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Effect of Heat Treatment on Microstructures and Mechanical Properties of Spring Steel

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Abstract

Oil quench and temper process offer enormous advantages to the heavy duty spring production because its treatment results can reveal optimum combination of toughness and ductility, and also improves fatigue life. The material used in this study was a commercial grade of heavy duty spring steel. Quench and temper process were used as a major heat treatment method. The resultant microstructures after quenching process are observed as martensite with small amount of retained austainite. After the tempering process, the resulting optimum mechanical properties are found at bainitic structure. In the hardening process, selective alloy was heated up to its austenitizing temperature, 870°C, and quenched in oil. After that, tempering was done at 450°C increased by 50°C to 550°C for each tempering time (1 hr, 2 hr, and 3 hr) interval. In this research work, microstructural examination, hardness, tensile and fatigue tests were done before and after tempering condition at room temperature. The experimental results revealed that mechanical properties of selective alloy were significantly changed by temper treatment. By increasing the tempering time and temperature, hardness and ultimate tensile strength are gradually decreased and ductility was improved. Moreover, rather interesting condition is observed in elastic properties and endurance limit at 450°C and one hour tempering condition, and this state is the optimum condition for spring production.

Key words : Oil quench, Tempering, Martensite, Retain austenite, Baitenite

Introduction

Today oil quenched and tempered springs are widely used for heavy duty spring where high mechanical properties are the main design driver. Major requirements of the spring steel are high yield strength, high proportional limit, and high fatigue strength. These desirable properties of spring can be achieved firstly by a higher carbon content or with suitable alloying elements, and secondly by heat treatment. Steel springs are used in hard, high strength condition. To attain these properties springs are hardened and tempered.

In the harden condition, the steel should have 100% martensite to attain maximum yield strength, but it is very brittle too, and thus, as quenched steels are used for very few engineering applications. By tempering process, the properties of quench steel could be modified to decrease hardness and increase ductility and impact strength gradually. Thus the formation of martensite provides a mechanical properties. The resulting microstructures are bainite or carbide precipitates in a matrix of ferrite depending on the tempering temperature.

Depending on the types of application, springs are made by carbon steels, silicon and manganese steels, silicon-manganese steels and stainless steels.

Methodology

Steels represent the most important group of engineering materials as they have widest diversity of applications of any of the engineering materials. The majority of the specifications are based on the chemical composition of the steels because it indicates the required heat treatment data, i.e. phase transformation temperatures and critical cooling rate of selective alloy. Therefore, any raw material that will be treated must be firstly analyzed to know chemical composition.

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The first step in the true heat treatment cycle of steel is the austenitizing. As a homogeneous distribution of carbon and alloying element is necessary to obtain uniform properties, it is used high austenitizing temperature and suitable soaking time in order to obtain a uniform distribution of carbon and alloying elements and to minimize the enrichment of impurity elements at the grain boundaries.

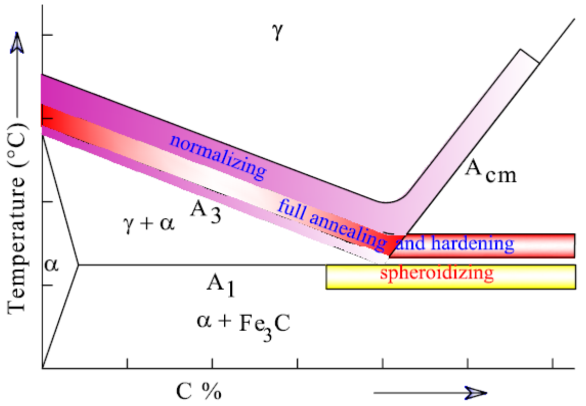

Figure 1. Normalizing, annealing and hardening temperature range for carbon steel(1)

The phase transformation temperature for low alloy steel with less than 0.6% C can be estimated by the following equations(2,3) and using heat treatment cycle for selective alloy is shown in Figure 2.

$$Ac_1 = 727 - 16.9Ni + 29.1Si + 6.38W - 10.7Mn + 16.9Cr + 290As \quad (1)$$

$$Ac_3 = 910 - 203\sqrt{C} + 44.7Si - 15.2Ni + 31.5Mo + 104V + 13.1W - 30Mn + 11Cr + 20Cu - 700P - 400Al - 120As - 400Ti \quad (2)$$

$$M_s = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 11Si - 7Mo \quad (3)$$

$$B_s = 830 - 270C - 90Mn - 37Ni - 70Cr - 83Mo \quad (4)$$

$$Log(CB) = 3.725C + 0.046Si + 0.626Mn + 0.706Cr + 0.52Mo + 0.026Ni + 0.675Cu - 1.818 \quad (5)$$

Ac_1 : Equilibrium Temperature of Austenitization Start [°C]

Ac_3 : Equilibrium Temperature for Austenitization End [°C]

Bs : Start Temperature of the Bainitic Transformation [°C]

Ms : Start Temperature of the Martensitic Transformation [°C]

CB : Maximum allowable cooling time to obtain martensite [sec]

For hypoeutectoid steels

Austenitizing temperature = Ac_3+ (20–40)°C

For hypereutectoid eutectoid steel

Austenitizing temperature = Ac_1+ (20–40)°C

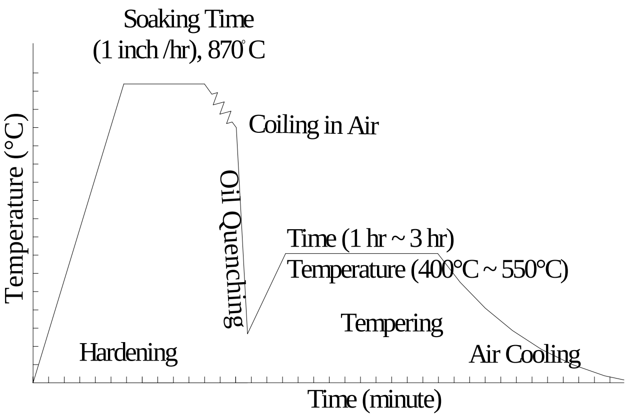

Figure 2. Heat Treatment Cycle for Spring Steel Treatment

The total heating time should be just enough to attain uniform temperature through the section of the part to enable not only the completion of phase transformation, but also to obtain homogeneous austenite. It should not be longer to cause grain growth, oxidation, and decarburization. Therefore the steel must be held at the hardening temperature as short a period of time as possible, generally calculated on the basic of one hour per inch of wire diameter.(4) Moreover, measures should be taken to prevent decarburization, though they are the simplest ones, such as covering the bottom of the furnace with charcoal or used carburizing compound.

After soaking at that hardening temperature, the steel specimen must be cold quenched at a rate faster than its critical cooling rate to attain martensite. After holding for the desired length of time in the hardening temperature, specimens are taken out for cooling in oil. The temperature of the quenching oil should be maintaining around 60°C.

The oil should have a good fluidity to increase heat transfer rate and it should be free from water.

The final step of this heat treatment cycle is tempering. Tempering is the process of heating the hardened steel to a temperature maximum up to lower critical temperature (A_1), soaking at this temperature, and then cooling, normally very slowly. The following four stages define the strength, hardness and toughness required in service application.(4)

1. *First stage of tempering* : Up to 200°C: Precipitation of ε (epsilon) carbide due to decrease of tetragonality of martensite,
2. *Second stage of tempering*: 200°C to 300°C: Decomposition of retained austenite.
3. *Third stage of tempering*: 200°C to 350°C: Formation of rod or plates of cementite with complete loss of tetragonality of martensite and dissolution of ε carbide.
4. *Fourth stage of tempering*: 350°C to 700°C: Coarsening and spheroidisation of cementite along with recovery and recrystallisation of ferrite.

The selective spring steel is tempered in the temperature range of 400°C~550°C in this paper. The desired properties and structures depend on tempering temperature and time.(5)

Materials and Experimental Procedures

Phase transformation temperatures and critical cooling rate for hardening treatment have been estimated from the chemical composition of the samples as shown in Figure 2.

Experimental heat treatment cycle for selective alloy is shown in Figure 2, and tempering conditions are done at 450°C increased by 50°C to 550°C for each tempering time (1 hr, 2 hr, and 3 hr) interval. After these treatments, treated specimens were examined its microstructure and mechanical properties i.e. hardness, tensile and fatigue testing.

Metallographic samples from all heat treatment conditions were prepared and etched in 2% nital in order to reveal the microstructures. Hardness measurements were performed using the Rockwell hardness testing machine. Indents were made on the polished surfaces using a 150 kg load for HRC scale and 10 sec dwell time.

Tensile tests were carried out by a universal testing machine (SM100) using JIS No. 14A test piece type specimens shown in Figure 3.

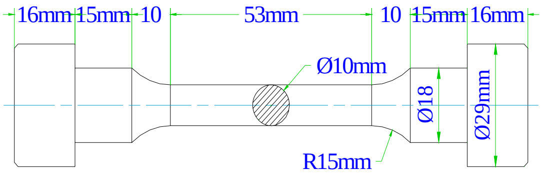

Figure 3. Tensile Specimen for SM100 Universal Testing Machine

Fatigue tests were performed using WP140 fatigue testing apparatus as illustrated in Figure 4. The sample was subjected to pure reversed bending stress in the machine.

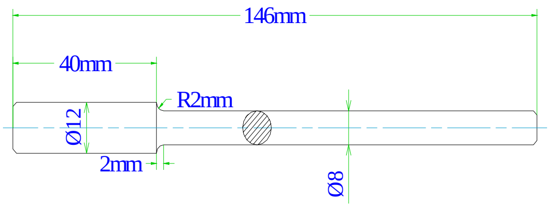

Figure 4. Fatigue Sample for WP140 Fatigue Machine

Moreover, Grossmann's critical diameter method(7) was used to determine maximum bar diameter and hardenability of selective alloy. There were five cylindrical test pieces with different diameter, 0.5 inch, 0.75 inch, 1 inch, 1.25 inch and 1.5 inch. In this method, a number of steel bars of different diameters were heated up to 870°C and then quenched. The length of each bar must be at least five times of the bar diameter to avoid end effects.(8) Then the samples were cut at mid position of bar length and measured hardness about 1/16 inch interval along each bar diameter across the center.

Results and Discussion

The chemical composition of test sample is C-0.52%, Cr-0.61%, Mn-0.7%, Si-0.21%, P-0.03%, S-0.04%. Its equivalent grade agrees with AISI-5155, 55Cr3 (DIN) standard specification.(5) This steel is suitable for high duty leaf springs, torsion bar springs and helical springs for vehicle construction.

Rockwell hardness for all heat treatment conditions are performed at room temperature and results are illustrated in Figure 5. There are two different significant trends in this graph because of changing of structural effect. Microstructures of oil and water quench of same steel are observed in Figure 6 and Figure 7, which contains martensite and retained austenite.

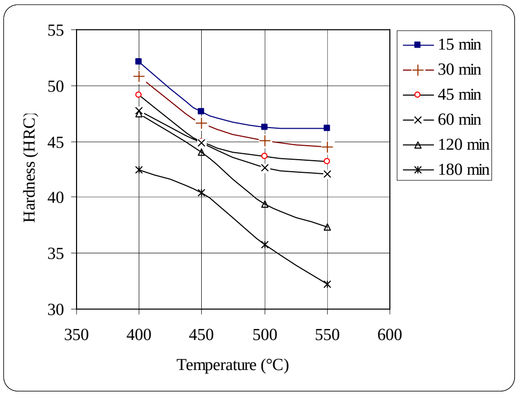

Figure 5. Effect of Tempering Time on the Hardness of Selective Alloy

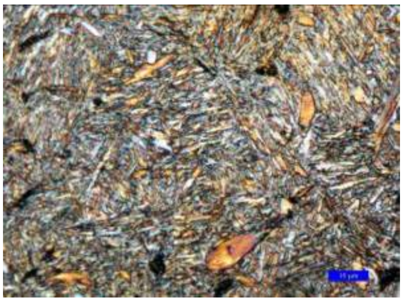

Figure 6. Microstructure of Selective Alloy for Oil Quench

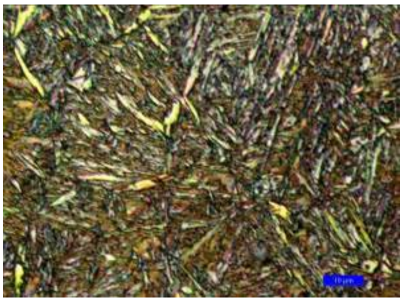

Figure 7. Microstructure of Same Steel for Water Quench

Moreover, the resulting tempered structures are expressed in Figure 8 to Figure 19. According to these microstructures, bainitic structure (ferrite and epsilon carbide) are formed at 400°C to 450°C for each tempering time, while cementite precipitate and ferrite matrix are observed at 500°C to 550°C. The growths of the size are observed tempering temperature and longer tempering time.

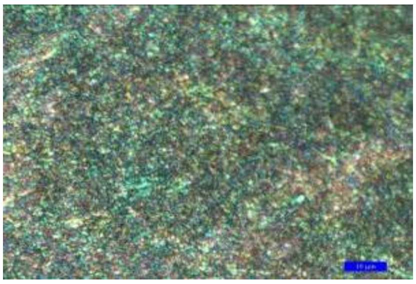

Figure 8. Oil Quench and Tempered at 400°C for 1 hr

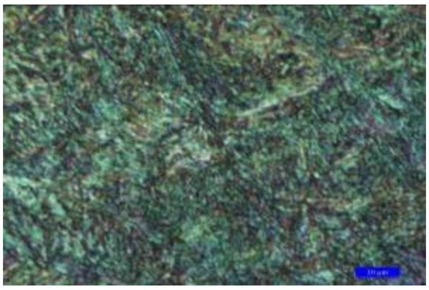

Figure 9. Oil Quench and Tempered at 450°C for 1 hr

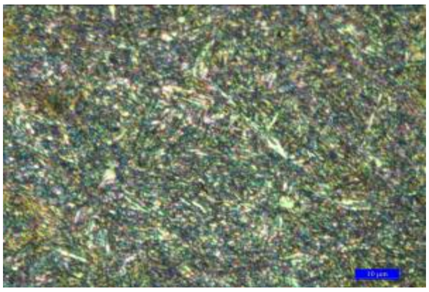

Figure 10. Oil Quench and Tempered at 500°C for 1 hr

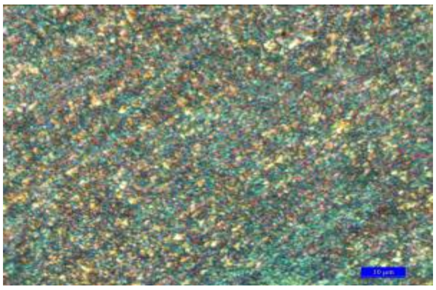

Figure 11. Oil Quench and Tempered at 550°C for 1 hr

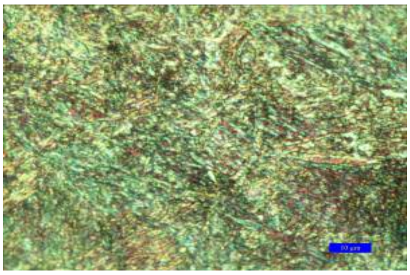

Figure 12. Oil Quench and Tempered at 400°C for 2 hr

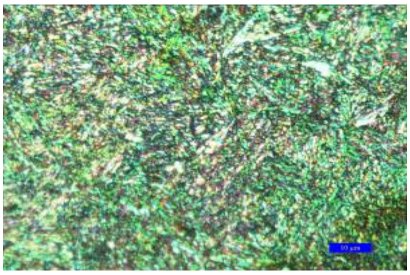

Figure 13. Oil Quench and Tempered at 450°C for 2 hr

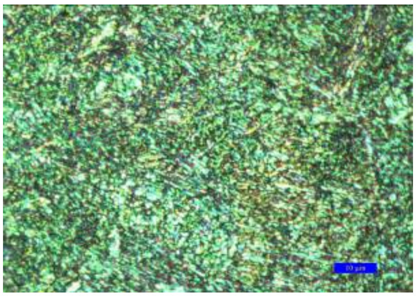

Figure 14. Oil Quench and Tempered at 500°C for 2 hr

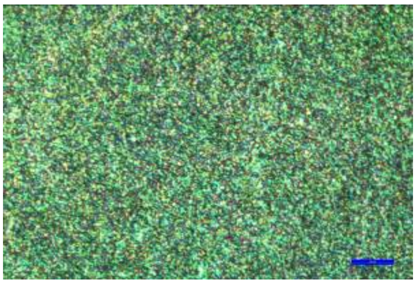

Figure 15. Oil Quench and Tempered at 550°C for 2 hr

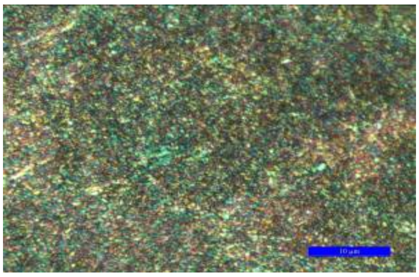

Figure 16. Oil Quench and Tempered at 400°C for 3 hr

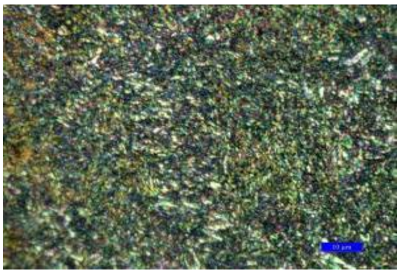

Figure 17. Oil Quench and Tempered at 450°C for 3 hr

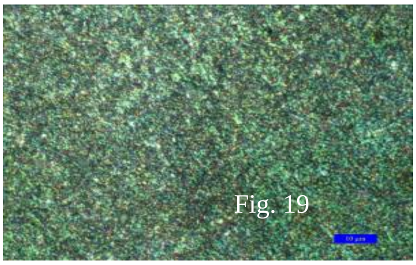

Figure 18. Oil Quench and Tempered at 500°C for 3 hr

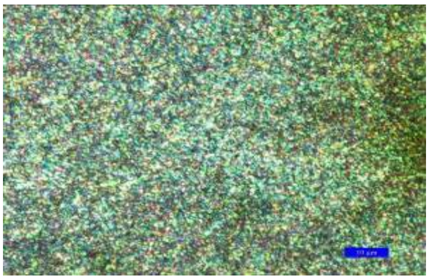

Figure 19. Oil Quench and Tempered at 550°C for 3 hr

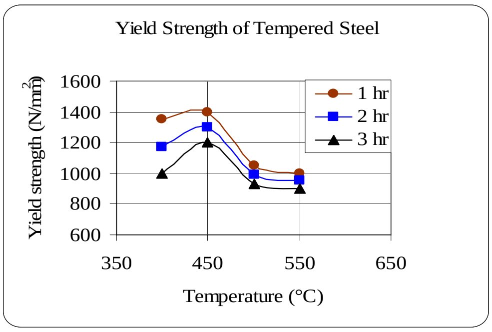

Figure 20. Variation of Yield Strength of Tempered Steel with Time and Temperature

For all treatment conditions, since the yield stress has been taken as the stress at 0.2% offset (9), no true yield point was observed in tensile tests. Any treatment method has virtually no effect on the modulus of elasticity of this alloy at room temperature.

Yield strengths are fluctuated by these tempering treatment conditions, which can be observed in Figure 20. It reaches peak point at 450°C for each tempering time, and then downward by increasing temperature. These maximum yield strength values are very important for spring production.

According to the structural point of view, retained austenite transforms to bainite at 400°C to 450°C. This alloy develops maximum elastic properties during this range and 450°C with one hour tempering treatment condition is best suited for spring production. After that yield strength values are steady decrease to 500°C and constant at 550°C. In the temperature range (500°C-550°C), the resultant microstructures are coarsening and spheroidisation of cementite along with recovery and recrystallization of ferrite. However, ultimate tensile strengths in Figure 21 are steadily decrease by increasing tempering time and temperature.

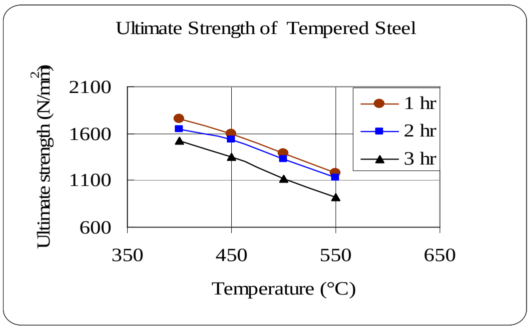

Figure 21. Variation of Ultimate tensile strength of tempered steel with time and temperature

The ductility of the samples are measured by the tensile test. The percent elongation shows upward trend in the increment of tempering time and temperature as shown in Figure 22. This graph indicates the degree of ductility of selective spring steel.

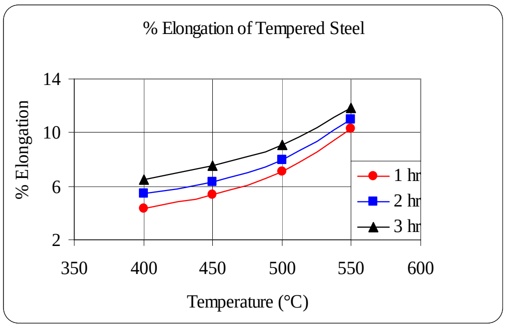

Figure 22. Variation of Percent elongation of tempered steel with time and temperature

A distribution of endurance limit is illustrated in Figure 23 indicating high endurance limit obtained at 400°C to 450°C. After these conditions, fatigue life decreased by increasing tempering time and temperature.

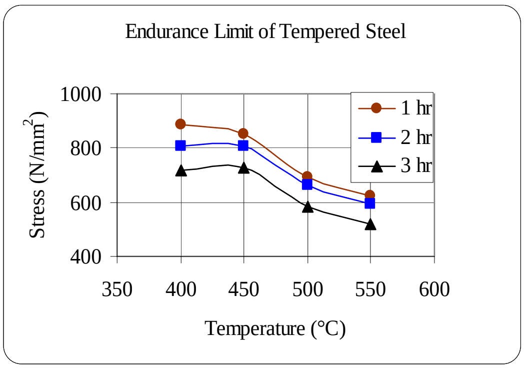

Figure 23. Variation of Endurance limit of tempered steel with time and temperature.

Effect of section thickness on the hardness of the oil quenched process are shown in Figure 24, as critical bar diameter should be taken round about 1.5 inch, the centre hardness of the bar to be about 50 HRC and circumference is 57 HRC. Therefore ideal critical diameter has been estimated as 2.7 inch by Grossman's critical diameter method with oil quenching intensity factor for moderate agitation (0.35 to 0.45) (8) from the result of Figure 24. Another method is used for hardenability value from chemical composition and grain size.(8) Grain size calculation method used in this paper is Jefferies Planimetric Test.(8) The resulting ASTM grain size number has been measured from Figure 25 as 6.453 and ideal critical diameter has been calculated as 2.5 inch using data from Figure 24 by composition method.(8)

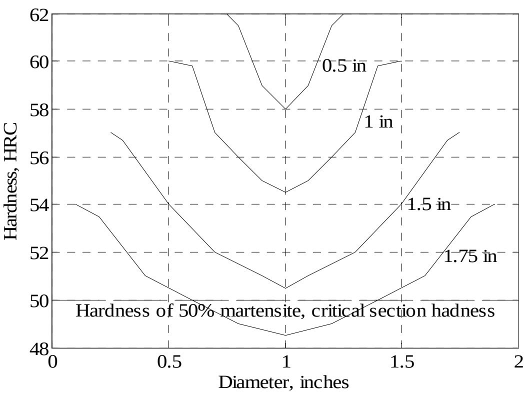

Figure 24. Effect of Section Thickness on the Hardness of the Oil Quenched Process

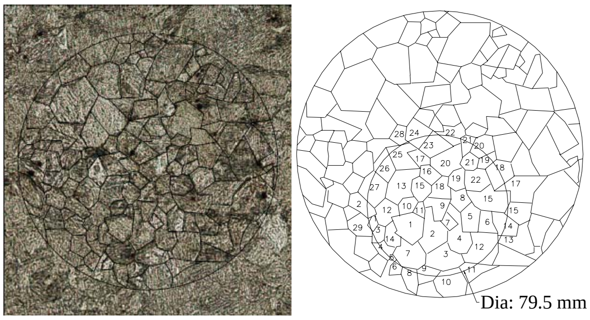

Figure 25. Grain Size of Selective Steel Bar

Conclusions

The following conclusion has been drawn from the experimental result and discussion already made.

1. Gradual decrease in hardness, ultimate tensile strength and increase in percent elongation of the as quench steel has been observed by increasing tempering time and temperature.

2. Peak point of the yield strength has been confirmed at tempering temperature 450°C.

3. Maximum fatigue life is observed at 400°C to 450°C.

4. From the structural point of view, more retain austenite are formed in oil quenching than in that of water. In tempered processes, ferrite and epsilon carbide are formed at 400°C to 450°C, and spheroid cementite are formed and grown above 450°C.

5. As ASTM grain size number is 6.453, the steel used is fine grain steel [4].

6. The ideal critical diameter of the selected bar has been calculated as 2.7 inch and 2.5 inch by Grossman’s method and chemical composition method.

7. The optimum bar diameter has been related as 1.5 in to obtain the required properties for oil quench and temper process.

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