EFFECT OF HEAT TREATMENT ON FATIGUE CHARACTERISTICS OF EN8 STEEL

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Abstract: - Fatigue failure is an important factor in most of the engineering applications, especially in steel materials, and among the steel materials, it is an important phenomena in medium carbon steels like EN8, which is very commonly used in components like shaft, gears etc., since it is prone to fatigue failure. Hence, without changing the composition, an attempt is made to enhance the fatigue strength by different heat treatment techniques. In this study, the investigation is carried out on heat treatment of EN8 steel material. Various kinds of heat treatment techniques like quench and temper, normalizing and annealing are performed on EN8 steel. After exposure to the heat treatment, the EN 8 steel material specimens are machined as per the ASTM standards and are subjected to RR MOORE test and SN-curves are plotted from the obtained results; the obtained results from the fatigue tests are further analyzed with the help of ANSYS software. Fatigue life and Factor of Safety (FOS) comparisons for EN 8 steel material is made with the structural steel material and it is found from the comparisons, that the heat treatment process enhances the fatigue strength and endurance limit.

Keywords: EN8 steel; Heat treatment; Fatigue strength; RR MOORE test; Basquin’s equation, Endurance limit.

1. Introduction

The admixture of iron and carbon is steel. Steel is classified as an iron carbon in which carbon content is within 2.11% and all those iron that contain above 2.11% of carbon are called cast iron. The admixture elements collective effect and heat treatment can result in large varieties of microstructure and properties [1]. Medium carbon steel has carbon content between 0.25 and 0.60. These admixtures may be heat treated by heating it to austenizing temperature, quenched, and then tempered to advance mechanical properties. They are frequently made practical in tempered condition having microstructure of tempered martensite [2]. The medium carbon steel material is profusely used in railway wheel and tracks, gears, crankshaft, axles, screws, cylinders [2, 3]. Fatigue strength is modified by the factors like material composition, heat treatment, operating temperature, grain size and grain direction, stress concentration, surface condition, size, residual stresses, fretting, corrosion, operating speed, strength reliability etc. [4, 5, 6] Grain size and its dispersion have a significant influence on yielding specificities of steel.

In this research, influence on fatigue strength due to heat treatment of EN 8 steel is studied. The materials are subjected to different heat treatment conditions like quenching, tempering, normalizing, and annealing. After heat treatment, materials are machined as per ASTM standards and RR MOORE test is accomplished; values obtained from the fatigue tests are plotted in SN graph and endurance limit is found and the endurance limit obtained by testing different heat treatment specimens are compared; after comparison, the heat treatment condition which influences the fatigue strength the most is identified. The values found are entered in ANSYS and fatigue analysis of shaft is accomplished.

2. Literature review

Extensive literature review in the domain of heat treatment of structural steel material is carried out to formulate the research plan; hence sufficient research findings of several researchers are referred to study the effect of heat treatment on fatigue characteristics of EN 8 steel.
Mooljane et al., [7] noticed that the grain size has very good impact on yield strength of steel. When the dispersion of grain is not uniform, the plastic deformation occurs more in weaker phase and stresses will be higher in stronger phase. The temperature and soaking time in annealing process has considerable effect on the grain size and phase dispersion. Among the metals, low cost metals are versatile in use because of its less expensive, convenient and economical production. Kareem et al., [8] has investigated consequence of heat treatment on fatigue strength of low carbon steel. The fatigue specimen was exposed to various heat treatments like annealing, normalizing and quenching before tests. The study concluded that annealed specimen has higher fatigue strength succeeded by specimen that is quenched in silica sand and normalized specimen. Phoumiphon et al., [9] had concluded that cold rolled specimen; when subjected to inter-critical annealing at different temperatures, there is increase in micro hardness and tensile strength; the research concluded that even though low carbon steel consists less pearlite, the inter-critical annealed specimen has better mechanical properties than as received specimen and cold rolled specimen. Li et al., [10] has demonstrated computational analysis of fatigue life of 0.44% carbon steel at various tempering temperatures. Two different methods estimating mean fatigue life are provided. One based on dislocation dipole accumulation and Paris law, another is Kringing model. The study concluded that the fatigue life decreased with increasing temperature. The dipole accumulation model was found to be more superior to the Kringing model. The fatigue crack growth behavior of hot rolled medium carbon steel specimens are studied by Mossaab et al., [11] after subjecting the specimen to heat treatment, they have concluded that refined microstructure is obtained by subjecting the specimens to different heat treatment conditions. The quenched specimen has higher strength compared to other heat treated samples. The normalized specimen exhibited higher malleability than other heat treated specimen. With increase in tempering temperatures there is decrease in hardenability. Heat treatment influences fatigue life, higher fatigue life is obtained after normalization treatment. For particular application, hardness is not preferred, because it lead to failure of component, so it is recommended to temper after normalizing. Sanusi et al., [13] has studied the modification of mechanical properties due to heat treatment. The result suggests that annealing and normalizing can result in drop of material’s ductility. The soaking time in furnace has an effect on surface finish. The soaking time also has effect on corrosion rate.

From the literature review, it is reported that the heat treatment has an influence on mechanical properties and microstructure, which has provided sufficient base for studying the effect of heat treatment on heat treatment characteristics of EN 8 steel.

3. Experimental details

3.1 Workpiece Materials

The type of steel used in this research is EN8 steel, and the chemical composition of material is shown in Table 1.

| Composition | Mn | P | C | S | Si | Fe |
|-------------|----|---|---|---|----|----|
| Amount in % | 0.77 | 0.02 | 0.42 | 0.02 | 0.22 | 98.55 |

The dimension of EN8 steel rod is as follows, diameter of the specimen of the steel rod is 15 mm, while the length of specimen of the steel rod is 250 mm; the total number of steel rods considered for studying the effect of heat treatment are 60 no.’s, with 10 steel rods each for the different heat treatment processes.

3.2 Heat Treatment Conditions

The effect of heat treatment on fatigue characteristics of the EN8 steel material is of prime concern, thus there is a need for subjecting the EN8 steel rods to different heat treatment conditions.
Figure 1., shows the procedure for heat treatment, the EN8 steel materials are exposed to process annealing, normalizing and quenching. First 10 numbers of the specimens are considered as it is, for unheat treated conditions, while the next 10 numbers of the specimens are heated to 650°C, soaked for 1 hour and allowed to cool in furnace and remaining 40 numbers are heated to 900°C soaked for 1 hour; out of these 40 numbers, 10 numbers of the specimens are allowed to cool in air and remaining 30 numbers of specimens are quenched in water.

Figure 1. Temperature v/s time diagram for process annealing, normalizing and quenching [14, 15]

Figure 2. Temperature v/s time diagrams for tempering [16, 17]

The procedures of tempering as shown in Figure 2, are followed. From 30 quenched EN8 steel, 10 numbers are heated to 300°C soaked for 1 hour, 10 numbers are heated to 450°C soaked for 1 hour, remaining 10 numbers are heated to 600°C soaked for 1 hour, and all the tempered specimens are cooled in air after soaking time.

3.3 Specimen Preparation for Testing

Materials are machined according to ASTM specifications, viz., ASTM F1160, ISO 1143. After machining, the materials are subjected to RR-MOORE test. Figure 3, shows the draft of the sketch of the specimen for fatigue tests.

Figure 3
3.4 Design Calculations

The set of the equations used for design calculations for the fatigue strength estimations of the un-heat treated and heat treated specimens are as follows,

Bending stresses, [19]

\[
\sigma_b = \frac{M_b}{I}
\]  

(1)

Where moment of inertia \( I \) for a circular cross section is

\[
I = \frac{\pi d^4}{64}
\]  

(2)

Positive maximum bending moment, [19, 20]

\[
M_B = \frac{1}{24} \times Wl
\]  

At \( x = \frac{1}{2} \)

(3)

Where \( W = w \times l \)

(4)

Negative maximum bending moment

\[
M_B = \frac{1}{12} \times Wl
\]  

(5)

c = distance from neutral fiber, for circular shaft \( c = \frac{d}{2} \)

Displacement at \( x = \frac{1}{2} \)

\[
y_{max} = -\frac{1}{24} \times \frac{Wx}{EI}
\]  

(6)

Goodman criteria [19, 20]

\[
\frac{2a}{S_a} + \frac{2b}{S_b} = \frac{1}{n}
\]  

(7)

Basquin’s equation [19, 20]

\[
\sigma_f = c_f (2N_f)^b
\]  

(8)

3.5 Analysis of Both Side Fixed Beam Using ANSYS Software

**Condition 1**

\( L = 2400 \text{ mm}, \, d = 50 \text{ mm} \)
Material: structural steel
Loading and support conditions
- Uniformly distributed load = 5 N/mm
- Both ends fixed support condition

**Condition 2**

The constraints and loading conditions are same as in condition 1; only material condition is considered to be tempered EN 8 steel at 300°C after hardening. For both the conditions, shear force, bending moment diagram, stresses, displacements and fatigue life, safety factors are estimated and the relative change in fatigue life after changing the material and constraints are determined.

4. Results and Discussions

The experiments were conducted for the unheat-treated and heat-treated specimens and the SN curves for fatigue strength were plotted to study the fatigue behavior of EN 8 steel specimens subjected to different heat treatment conditions.

4.1 SN curves from experiments for different heat treatment conditions

The SN Curves from experiment for different heat treatment conditions on the EN 8 specimens are depicted in the **Figure 5**.

![Figure 5. SN curves for different heat treated specimens](image)

**Figure 5.** SN curves for different heat treated specimens

**Figure 5.** shows the SN graphs for stress in MPa v/s Number of cycles of non-heat treated specimen and heat treated specimens; further, for the unheat-treated specimens, it is observed that the endurance limit is 306 MPa at 1.26 E+06 cycles and the fatigue stress, which is calculated from the basquin’s equation is 311.46 MPa.

\[
\sigma_f = 306 \text{ MPa}, \quad N_f = 1.26 \times 10^6 \text{ cycles} \quad (9)
\]

\[
b = \frac{\Delta \sigma}{\Delta N_f} = -0.112033 \quad (10)
\]
From Basquin’s equation

$$\sigma_f = 328 \left( \frac{7.94E+08}{5.01E+08} \right)^{-0.1152058} = 311.46 \text{ MPa} \quad (11)$$

Similarly, the fatigue stress is calculated from basquins equation for other heat treated specimens, and the results are tabulated. The table 2 gives the experimental and numerical fatigue limit of specimens for different heat treatment conditions.

| Heat Treatment Condition | EXPERIMENT Fatigue limit (MPa) | Fatigue limit from BASQUIN equation MPa | Error in % |
|--------------------------|---------------------------------|----------------------------------------|------------|
| Non heat treated         | 306                             | 311.46                                 | -1.78      |
| Process annealed         | 323                             | 321.70                                 | 0.4        |
| Normalization            | 364                             | 357.13                                 | 1.88       |
| Temper 600°C             | 370                             | 376.92                                 | -1.87      |
| Temper 450°C             | 407                             | 411.97                                 | -1.22      |
| Tempering, 300°C         | 483                             | 489.4                                  | -1.32      |

Figure 6. Comparison of fatigue limit of specimens subjected to different heat treatment conditions.

Figure 6, shows the comparison of fatigue limit for specimens subjected to different heat treatment conditions, the result shows that fatigue strength increases after heat treatment. It is clear that EN 8 steel tempered at 300°C has a fatigue limit of 483 MPa which is high when compared to non-heat treated specimens and the specimens subjected to other heat treatment conditions.

4.2 Fracture Studies

Figure 7, shows the optical fractographs of fatigue cracked specimens. One of the main features associated with fatigue crack growth is the appearance of fatigue striations. Striations are identified by distinct ridges, grooves and channels [21]. While such marks are due to crack extension probably by fatigue growth, the mechanism of formation requires the hard inclusions, combined mode 1(tension) and 2(shear direction of crack growth) or mode 1(tension) and 3(shear direction perpendicular to crack) [22, 23]. These marks are called the tyre tracks which are visible in untreated steel specimens [24, 25]; however, these are not distinctly visible in heat treated specimens due to micro-coring and segregation among the residual atoms in the steel solutionized phases [26].
4.3 Analysis of Beam Using ANSYS

The analysis of beam is carried out using ANSYS for different end conditions and the comparative evaluation of the results are accomplished for structural steel and EN 8 steel.

The analysis of beam is carried out for 2 ends fixed condition for structural steel and EN 8 steel material tempered at 300°C conditions.
Analysis of beam fixed at 2 ends (Structural Steel)

Figure 8. Fatigue life of beam fixed at 2 ends

Figure 9. FOS of beam fixed at 2 ends
Table 3. Comparison of the results of a beam fixed at 2 ends

| Material                          | Structural steel | Calculations | ANSYS      |
|-----------------------------------|------------------|--------------|------------|
| Total load                        | 12000 N          | 12000 N      |            |
| Positive maximum bending moment   | $1.2 \times 10^6$ Nmm | $1.2 \times 10^6$ Nmm |            |
| Negative maximum bending moment   | $2.4 \times 10^6$ Nmm | $2.4 \times 10^6$ Nmm |            |
| Maximum Bending Stresses          | 195.56 MPa       | 195.97 MPa   |            |
| Displacement                      | 7.04 mm          | 7.08 mm      |            |
| Life (no. of cycles)              | -                | 29424        |            |
| F.O.S(min)                        | 0.44             | 0.44         |            |

Analysis of beam fixed at 2 ends (material conditions EN8 steel tempered at 300°C)

Figure 10. Fatigue life of beam fixed at 2 ends
Table 4. Comparison of the results of a beam (material EN 8 steel tempered at 300°C) fixed at 2 ends

| Material                              | Calculations         | ANSYS          |
|---------------------------------------|----------------------|----------------|
| Total load                            | 12000 N              | 12000 N        |
| Positive maximum bending moment       | 1.2×10⁶ Nmm          | 1.2×10⁶ Nmm    |
| Negative maximum bending moment       | 2.4×10⁷ Nmm          | 2.4×10⁷ Nmm    |
| Maximum Bending Stresses              |                      |                |
| Displacement                          | 6.70 mm              | 6.75 mm        |
| Life (no. of cycles)                  |                      |                |
| F.O.S(min)                            | 1.58                 | 1.58           |

Table 5. Comparison of fatigue life and FOS for different materials and conditions

| Fatigue parameters                   | Structural steel fixed at 2 points | EN 8 steel tempered at 300°C for 1 hour, fixed at 2 points |
|--------------------------------------|-----------------------------------|----------------------------------------------------------|
| Life (no. of cycles)                 | 29424                             | 1.45×10⁶                                                 |
| F.O.S(min)                           | 0.4475                            | 1.58                                                     |

Life estimation of the specimens was carried out using the RR Moore fatigue test, for “as brought” and “heat treated” conditions like annealing, normalizing, and tempering at 300°C, 450°C and 600°C. After plotting the obtained values in a graph, it is observed that fatigue strength of annealed specimen is higher than untreated specimen, i.e., 323 MPa. Normalized specimen has higher fatigue limit when compared to annealed specimen i.e., 364 MPa. When compared to normalized specimen, the tempered specimen at 600°C, 1 hour, has fatigue limit of 370 MPa, while the tempered specimen at 450°C, 1 hour has fatigue limit of 407 MPa; the tempered specimen at 300°C, 1 hour, has
a fatigue limit of 483 MPa. Thus, the EN8 Steel tempered at 300°C is considered for analytical evaluation and subsequent comparison with the structural steel material.

Analysis of beam at uniformly distributed load condition for structural steel gives a fatigue life of 29424 cycles and FOS of 0.4475.

For the improvement of fatigue life of the beam, two end support condition is considered from the initial trial and error in ANSYS software, which shows improvement in fatigue life and FOS i.e., the application of two end fixed boundary condition gives a fatigue life of 1×10^6 cycles and FOS of 1.7. Improvement of fatigue life and factor of safety is observed, when material is changed, i.e., for EN 8 tempered steel fixed at 2 ends; the fatigue life is 1.45×10^6 cycles and FOS is 1.58, the bending stress 195.56 MPa is within safety limit, since the yield limit for EN8 tempered steel is 255 MPa.

5. Conclusions

The conclusions for the effect of heat treatment on fatigue strength of EN 8 steel is discussed with respect to the fatigue strength and subsequently, the improvement of life and factor of safety of EN 8 steel beam fixed at two points is validated with computational results obtained from ANSYS software.

Conclusions for the effect of heat treatment on Fatigue Strength

- It is observed from the experimental results that the fatigue strength increases after heat treatment.
- It is clearly seen from the results, that the fatigue strength is high for tempering as compared to other heat treated specimens.
- In tempering, one which is tempered at lower temperature i.e., 300°C has high fatigue strength compared to other tempered specimens.
- It is found that heat treatment can increase fatigue strength and life of the EN8 steel material along with other properties viz., FOS for the material.
- It is concluded that, Basquin’s equation can be used to predict endurance limit from the values of test.

Analysis of Beam fixed at two ends

- If supports are used, fatigue life and FOS increases but usually supports can add weight and will modify the design because additional brackets and bearing is needed, that will sometimes increase maintenance.
- By change of material from structural steel to EN8 steel, fatigue strength and FOS are increased, while the bending stresses are within the allowable stress limit.

Thus, the EN8 steel with effective heat treatment viz., tempering at 300°C can be used for structural applications requiring better fatigue life, when subjected to cyclical loading in their routine operations.

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