Effect of Heat Treatment on Toughness and Fatigue Behavior Strength of Steel CK45

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Abstract: The function of the axle drive shaft is to transfer the engine torque from the gearbox or differential gear to the wheels. It must also endure for all dynamic loads resulted from variations in angle or length during driving from contact the vehicle tire with road. Most problems with the axle drive shaft manifest themselves in the form of knocking noises when driving around tight corners, accelerating, or when the suspension is being compressed and extended where the drive shaft becomes weakened and more subject to stress failure due to dynamic torsion, tensile, shear, and compression. This work consists of effect of heat treatment type applied to the steels CK45 on the resulted behavior of the fatigue and toughness and study of these heat treatments on the microstructure and micro-hardness across the specimens depth. Where this heat treatable alloy usually used in drive-shafts in vehicles which exposed to a dynamic loads and the goal is to investigate the best relation between heat treatment and the service conditions. However, microstructural characterization and microhardness measurements revealed that the shaft belongs to medium carbon steel contains ferrite and pearlite, measuring the toughness for four heat treatments to obtain the best case and measuring the fatigue life of quenching case has better life compared to other cases. The oil quenching gives best toughness value of 30 KJ/m² and the worst value obtained for as received one giving 7 KJ/m² and the maximum fatigue life under stress of 375 MPa belonged to oil quenching treatment and it was 75000 cycles to failure while the as-received alloy reported 2000 cycles at failure. The S-N curve of the four cases based on Basquin formula with correlation factor (R²) close to one. And the water quenching steel alloy recorded higher curve component to other cases.

1. Introduction and literature review:
The mechanical properties of light carbon steel (CK45) and fatigue behavior were studied in heat treatment processes. The fatigue strength of the treated samples at 450 °C is approximately 2 times more than the untreated samples. In addition, the fatigue limit does not increase with temperature and has a choice point, in other words further heating above 450 °C does not increase the fatigue power significantly. This increase in fatigue strength is due to the bi-stage microstructure that is altered through the processing processes. The configuration of the double-phase microstructure can delay the start and start of the crack.[5] The gas quenching procedure following low-pressure carburizing differs from the
conventional procedure of gas carburizing and oil quenching. It is shown that the introduction of a holding time during the low-temperature part of the quench has a positive effect on mechanical properties, with some 20 percent increase in fatigue strength. This is attributed to increased compressive surface residual stress and stabilization of austenite. This research comprises a study of the effect of heat treatment on fatigue behavior of (A193-51T-B7) alloy steel. Two heat treatment processes were conducted, namely, annealing and quenching followed by tempering at 200°C. All fatigue tests were carried out using a rotary bending machine with constant stress ratio, $R=-1$. The eddy current probe was used to measure the crack length propagation. From the obtained results, it was found that fatigue crack growth rate of the quenched and tempered specimens is lower than that of the standard specimens. While the fatigue crack growth rate of the annealed specimens is higher than that of the standard specimens.[9]. Analysis of fatigue of steel alloys CK35 based on deviation and ANN technique. Two groups of tests have been designed. The first group was examined at constant amplitude fatigue loading, and the second group was tested under variable cumulative fatigue loading. The proposed model was compared with other cumulative fatigue theories and the results show that the proposed model predicts closer lives compared to the experimental lives. The ANN predictions of fatigue life show an average percentage error less than 3% for cumulative fatigue loading.[10] Tempering is a common manufacturing process step following hardening in order to increase the toughness of the steel. However, the research shows that the higher hardness from eliminating tempering from the manufacturing process is beneficial for contact fatigue resistance. The untampered steel showed not only less contact fatigue damage but also a different contact fatigue mechanism.[6]. low cycle fatigue life of CK45 steel and SS316 stainless steel under strain controlled loading are experimentally investigated. Furthermore, it is attempted to predict fatigue life using energy and SWT damage parameters. The experimental results demonstrate that increase in strain amplitude decreases fatigue life for both materials, strain amplitude has a remarkable effect on fatigue life, and the impact of mean strain is approximately negligible.[7] The present work aims to investigate the influence of different heat treatments on toughness and fatigue behavior of CK45 steel alloy under room temperature (RT).

2. Experimental work:
The metal used in this work is a medium carbon steel Ck45 according to the German specification standard (DIN) which used in drive shaft in cars. The goal of the work is to find the optimum treatments to produce high mechanical properties applied for this item in service conditions such as toughness, fatigue life and surface hardness to serve good wear resistance. The sampling process includes cutting the drive shaft with samples of long 100 mm and diameter of 25 mm. The raw samples machined to two types of tests. For fatigue test rounded specimen was manufactured according to standard ASTM standard E606/E606M-12 and Charpy Impact test samples according to ASTM E23-01a as shown in figure (1).
Figure 1. Impact test specimen According to ASTM A370,[14] the standard specimen size for Charpy impact testing is 10 mm × 10mm × 55mm.

Figure 2. Fatigue test Machine
The chemical analysis of the selected drive shaft illustrated in Table 1 showing the shaft material is related to CK45 steel type which is a medium carbon steel accepted heat treatments. Before machining the drive shaft to a specimens it is annealed by maintaining in electric furnace at 910°C for two hours then it leaved in furnace until cool down to room temperature to anneal the shaft to its original condition without any modified microstructure. The heat treatments include Annealing, Normalizing, Hardening and Tempering.

The chemical analysis of the steel alloy Sk45 done by the Central Organization for Standardization and Quality Control is an agency of the Government of Iraq, table 1 represents chemical analysis.

### Table 1. Chemical composition of the selected drive shaft.

| ChemicalComposition | Element Wt%of CK45 | ChemicalComposition | Element Wt%of CK45 |
|---------------------|-------------------|---------------------|-------------------|
| C - carbon          | 0.453             | Ni - Nickel         | < 0.0010          |
| Mn - Manganese      | 0.644             | Ti - Titanium       | < 0.0010          |
| Si - Silicon        | 0.247             | Cr - Chromium       | 0.0010            |
| Cu - Copper         | 0.169             | Ca - Calcium        | 0.0009            |
| Sn - Tin            | 0.0319            | Al – Aluminum       | 0.0010            |
| Mo – Molybdenum     | 0.0248            | Others              | 0.005             |
| S - Sulphur         | 0.0040            | Remaining Fe – Iron | 98.4224           |

3. Results and discussion:

3.1 Impact and fatigue tests:
The impact test and the fatigue test were performed on the four samples used in the study and the results were as shown in Table 2.
Table 2. Impact and fatigue life for five minutes at 375 MPa applied stress for various heat treatments.

| No. | Type of heat treatment   | CharpyImpact test (kJ/m²) | Fatigue test at 375 Mpa stress and 1350 RPM for five minutes |
|-----|-------------------------|---------------------------|-------------------------------------------------------------|
| 1   | As- Received            | 7.0                       | 20000                                                       |
| 2   | Air Normalizing         | 9.2                       | 50000                                                       |
| 3   | Oil quenching           | 30.0                      | 75000                                                       |
| 4   | Water quenching         | 10.5                      | 11000                                                       |

The above heat treatment may be denoted by the number as:

(1) As- Received.

(2) Air Normalizing.

(3) Oil quenching.

(4) Water quenching.

Figure 4. The variation of Impact energy and fatigue life at constant applied stress level for four types of heat treatment.

3.2 Constant S-N Curves:

In the present work, rotating bending fatigue tests were conducted for Ck45. Constant amplitude tests were done for six stress levels, 400, 375, 350, 300, 250 and 200 MPa to evaluate the stress-No. of cycles to failure curve or S – N curve for four cases mentioned before. The experimental results are tabulated in a Table (3).
Table 3. Constant fatigue test results for four cases of heat treatments

| $\sigma_f$ (Mpa) | (1) $N_{far.}$ cycles | (2) $N_{far.}$ cycles | (3) $N_{far.}$ cycles | (4) $N_{far.}$ cycles |
|-----------------|------------------------|------------------------|------------------------|------------------------|
| 400             | 2668                   | 6647                   | 10401                  | 586                    |
| 375             | 4005                   | 10013                  | 15071                  | 1003                   |
| 350             | 6185                   | 15517                  | 22406                  | 1782                   |
| 300             | 16326                  | 41292                  | 54339                  | 6431                   |
| 250             | 51465                  | 131402                 | 154943                 | 29349                  |
| 200             | 209786                 | 541882                 | 558633                 | 188152                 |

*Three specimens were tested for each stress level and the average life (cycles).

Figure 5. Constant fatigue test curves for four cases of heat treatments

To carry out a fatigue test, the specimens are loaded into rotating beam fatigue testing with stress ratio (-1).

The mean S-N curve can be described by Basquin equation $\sigma_f = AN_f^{\alpha}$, where $A$ and $\alpha$ are material constants determined experimentally. Table (4) gives the values of $A$ and $\alpha$ for the above cases of heat treatments.

Table 4. given the constants $A$ and $\alpha$ with the correlation factor $R^2$.

| $A$  | $\alpha$ | Basquin equation | $R^2$  |
|------|----------|------------------|--------|
| 1400 | -0.1588  | $\sigma_f = 1400 N_f^{-0.1588}$ | 0.926  |
| 1600 | -0.1575  | $\sigma_f = 1600 N_f^{-0.1575}$ | 0.97   |
| 200  | -0.1740  | $\sigma_f = 200 N_f^{-0.174}$  | 0.94   |
| 860  | -0.1201  | $\sigma_f = 860 N_f^{-0.1201}$ | 0.96   |

4. Cumulative fatigue results:

Many structural components experience variable amplitude load histories containing over load and underload cycles such as harsh maneuvers during flight, hard landings, the oldest theory for evaluation cumulative fatigue is the palmgram-maner liner hypothesis [8]. According to this rule, the s-n curve properties (basquakeqution) be obtained and it is assumed that the damage takes linear manner during working. The miner rule can be summarized as:
Where \( K \) denotes the number of steps in the program and \( i \) is the number of program iteration until failure. Applying Miner rule for experimental data table (5) gives the results of \( N_f(\text{Miner}) \) in comparison with the experimental results. The application of Miner rule can be described in appendix (1).

**Table 5.** Application of Miner rule for cumulative fatigue for four types of heat treatment.

| Loading sequence | (1) \( N_{far} \) | (2) \( N_{far} \) | (3) \( N_{far} \) | (4) \( N_{far} \) |
|------------------|------------------|------------------|------------------|------------------|
| \( L - H \) 250 - 350 | 8200             | 20600            | 27800            | 2050             |
| \( H - L \) 350 - 250 | 5220             | 16800            | 21200            | 1680             |
| \( N_{f_{\text{miner}}} \) | 11042            | 27758            | 39151            | 3178             |

**Figure 6.** The microstructure of annealed ck45 steel specimens.
In figure (6) from optical microscopic images (a and b) the microstructure indicates that the structure belongs to medium carbon steel contain ferrite as bright grains and perlite as dark grains. The grain size about (10-15 μm).

The fracture analysis of impact test in figure (6-c) shows full ductile fracture topography begins from the impact surface till the point of separation with some nicking and full dimpled structure appear in fractography as showed in figure (6-d).

![Figure 6](image_url)

**Figure 7.** Microstructure of normalized specimen (a, b) at near surface region and (c, d) at the specimen center.

Normalizing the CK45 by Air cooling change the microstructure of coarse perlite to very fine perlite granins as indicated in figure (7) where (a,b) images showing the structure at specimen center while image (c and d) showing the structure at the edge of the specimen.

The fracture analysis of Air cooling shows different fractography from the annealed specimen and the fracture begin around circumstance of specimen as shown in figure (8-a) in hardened region figure (8-b) then finally directed to the center where fracture nature was ductile (dimpled) shown as in figure (8-c).

Figure (9): represent fracture of water quenching specimen where it is clear the brittle fracture is the dominant without nicking in specimen as
Figure 8. Fractography behavior of ck45 after normalizing in Air (a) some dimpled ductile fracture and river pattern brittle fracture near surface (b) dimple fracture region in center of specimen (c).

Figure 9. Fractography behavior of ck45 after water quenching (a) trans-granular brittle fracture (b) dimple-trans fracture region in center of specimen (c).

shown in (a) where in (b) the fracture is purely intergranular fracture but in (c) in center of specimen there is small dimple areas with intergranular major fracture behavior. In Figure (10) the optical microscope image show full martensitic grains which indicates that the water quenching transform ala austenite to martensite without sufficient time to separating carbon to perlite. So, the general specimen behavior here is brittle.
Finally, oil quenching shows considerable differ fracture mechanics from water where there is nicking in fracture region as shown in figure (11-a) and image (b) near surface show mostly ductile fracture as it happened in the specimen center in image (c). In figure (12), the oil quenching microstructure show some martensitic structure with bainite which give the metal good toughness with considerable hardness.

Figure 10. Optical microstructure image for water quenching specimen section.

Figure 11. Fractography behavior of ck45 after oil quenching (a) specimen fracture with some nicking (b) dimple fracture near edge (c) dimple fracture region in center of specimen (c).

Figure 12. Optical microstructure image for oil quenching specimen section.
5. Conclusions:

Toughness and fatigue life of steel CK45 treated by four types of heat treatments was investigated experimentally. The following conclusion may be drawn from this work.

1) The toughness of the four heat treatments i.e. (as received, air normalizing, oil quenching and water quenching) was obtained by impact test. The experimental results observed that the oil quenching steel alloy CK45 was the best alloy showing 30 KJ/m² toughness and the worst case was obtained for as received one giving 7 KJ/m² toughness.

2) Experimental results indicated that the fatigue life of oil quenching case has better life compared to other cases and the fatigue life of 375 MPa recorded 75000 cycles to failure while the as-received alloy reported 2000 cycles at failure.

3) The S-N curve of the four cases established experimentally and based on Basquin formula with correlation factor (R²) close to one. The results revealed that the water quenching steel alloy recorded higher curve component to other cases.

4) Miner rule was applied to cumulative fatigue life carried experimentally (Low – High and high-low block stresses) for predicting the cumulative fatigue life for all the four cases studied.

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