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Study the Effect of Quenching and Tempering Conditions on the Fatigue Coefficients for Low Carbon Steel

Azzam D. Hassan [1,*], Safaa A. S. Almtori [2], Atef Nema [3]

[1,2,3] *Department of Material Engineering, College of Engineering, University of Basrah, Basrah, Iraq*
E-mail addresses: azzam.hassan@uobasrah.edu.iq , safaa.saleh@uobasrah.edu.iq , atef.jarad@uobasrah.edu.iq
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Abstract

Four groups of AISI 1020 specimens were heat-treated at 850 °C in a muffle furnace for 30 minutes then quenched in oil. The samples were tempered at 400 °C with a time period for each group as (group B, 2 hours), (group C, 3 hours), and (group D, 4 hours). The mechanical properties of the samples were studied using universal tensile testing equipment and a Brinell hardness testing machine. The hardness values of the quenched samples were calculated from a given modified equation. The torsional fatigue behavior of AISI 1020 was discovered in this investigation for heat-treated specimens and compared with the original specimens. All groups were subjected to an analysis using an optical microscope. Pearlite is formed when is heated in the austenitic region and then cooled below a lower critical temperature. It was concluded that the heat treatment increases the hardness for the specimens while decreased the shear fatigue ductility coefficient. Also, the heat treatment increased the shear fatigue strength coefficient. Furthermore, increasing in the time period of the tempering process was leaded to decrease the coefficient of shear fatigue strength and increased the coefficient of shear fatigue ductility.

Keywords: Quenching, Tempering, Shear fatigue properties, AISI 1020.

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1. Introduction

With the growing demand from many industries for steel with outstanding mechanical qualities to be used in a variety of applications, it was vital to understand the failure that would occur to the steel during both quenching and tempering.

Quenching and tempering are heat treatment procedures that are used in the manufacturing industry. To modify a material's physical and chemical properties, thermal and metalworking procedures are applied and are utilized in the production of a variety of different materials. The method of heating or cooling a metal to a certain temperature, usually to attain the desired result such as hardening or softening, is referred to as heat treatment. Heat treatment processes include annealing, case hardening, precipitation strengthening, tempering, carburizing, normalizing, and quenching. Although the phrase "heat treatment" refers to techniques in which the purpose of heating and cooling is to change the qualities of the material, heating and cooling frequently occur as a byproduct of other industrial processes such as hot forming or welding. Many studies were done on the effects of quenching and tempering, which can be illustrated as Chen et al. [1] studied the microstructure and mechanical properties of a 30MnBNbV steel for hot stamping after complete austenitization by quenching at different temperatures (30 °C, 230 °C, 300 °C).

A sequence of laboratory studies on the quenching and heating system of the Q1030 ultra-high-strength have been conducted by Wang et al. [2], the grain development model has been constructed, and the computation of regression method has been used to verify the model's validity. Some important manufacturing factors were modeled. The heat treatment system of Q1030 super high strength engineering machinery steel is investigated, and several essential production simulation parameters are studied. The influence of alloying elements on tissue transformation, as well as the heat treatment microstructure and strength evolution at various austenitic temperatures was investigated and providing a foundation for the actual manufacture of Q1030 ultra-high-strength steel.

The microstructure and hardness of HMSS 8Cr13MoV at various quenching settings were investigated by Zhu et al. [3]. When compared to oil-quenched samples, air-quenched samples have less residual austenite, a more compact microstructure, and higher hardness. The martensitic transition occurs in HMSS at a slow nucleation rate in a few isolated locations. Senthilkumar and Ajiboye [4] examined the impact of heat treatment on the mechanical properties of medium carbon steel in order to ensure that the steel is better suited structurally and physically for those working in steel product design, manufacture, and maintenance.

Mudashiru et al. [5] investigated the mechanical behavior of the samples following heat treatment at 900 °C in a muffle furnace for 1 hour before quenching in a poll of water maintained at 10, 20, 30, 40, and 50 °C. The samples were tested for tensile strength and hardness using a universal tensile testing machine and a Brinell hardness machine. When compared to unquenched samples, samples quenched in the water had better mechanical characteristics.

Shamsaei and Fatemi [6] studied the cyclic deformations and fatigue behavior of 1050 steel case-hardened solid specimens in torsion. Based on the core and case materials' uniaxial characteristics. The Von Mises criterion was discovered to be accurate in predicting shear cyclic deformation. The maximum main strain criteria were used to estimate shear fatigue parameters from uniaxial properties, and the findings were in good agreement with those of the experiments.

The goal of this research is to discover the Fatigue Limits of Medium Alloy Steel and to do so by quenching and tempering groups of samples at different temperatures. In general, the goal of failure measurement is to aid in assessing the extent of a material's exploitation for a variety of applications.

2. Materials and Methods

2.1. Quenching Process

The quenching process is a type of metal heat treatment. The process of rapidly cooling metal in order to regain its original mechanical properties is known as quenching. A metal is heated to a temperature higher than typical for the quenching process, usually halfway between its recrystallization and melting temperatures [7]. To allow the heat to "soak" into the metal, it might be held at this temperature for a set period of time. After being held at the desired temperature, the metal is quenched till it reaches room temperature in a medium. The metal can also be quenched for a longer amount of time to ensure that the material is cooled across its whole thickness during the process.

Steel shafts with a length of 160 cm and a diameter of 14 mm were sliced into 16 samples, each with a length of 10 cm. The pieces are divided into four groups (A, B, C, and D), each of which has four samples, Fig. 1 shows the situation. The parts were subjected to several mechanical procedures in order to get the requisite shape for the torsional fatigue test.

Fig. 1 Groups of the samples.

2.2. Tempering Process

Tempering is a heat-treating procedure that improves the toughness of iron-based alloys. After hardening, tempering is used to reduce some of the extra hardness by heating the metal to a temperature below the critical point for a period of time and then cooling in still air. The amount of hardness reduced is determined by the exact temperature, which is dependent on both the alloy's composition and the desired qualities in the completed product. Hard tools, for example, are frequently tempered at low temperatures, whereas springs are tempered at much greater temperatures [8].

2.3. Fatigue Process

It has been used a variety of approaches to determine the fatigue life of a material such as the stress-life technique and the strain-life technique. The present study found the fatigue behavior for AISI 1020 based on the strain life method using a modified equation.

2.4. Hardness

In evaluating the mechanical properties of metallic materials, mechanical hardness testing is essential. The hardness (Brinell and Vickers) of the original samples was assessed to provide a preliminary assessment of the material employed in this study [9].

The equipment that used to conduct hardness test was Model HV-30, Serial No. V1528, Jinan Kason Equipment Co, Ltd. It is necessary to ensure that sample material is correctly prepared and that the surface of the specimen to be tested is prepared and polished before entering it into the hardness testing equipment. The load utilized determines the surface condition necessary for the Vickers hardness test. Under a weight of 1 to 100 kgf, a diamond indenter in the shape of a right pyramid with a square base and a 136-degree angle between opposed faces indents the test material. The full load is applied for 10 to 15 seconds in most cases. For greater precision, multiple readings were taken, see Table 1.

Table 1. Vickers results of tests.

Hardness	Readings	Average
HV	215 / 220.5	217.7
HB	188 / 191	198.5

2.5. Chemical Composition

The chemical composition of the AISI 1020 Steel utilized in this study was carried out and listed as illustrated in Table 2. The mechanical and the characteristics physical properties are tabulated in Table 3 for the specimens used in this study.

Table 2. Chemical composition for material.

Components	ASTM A29	Measured
C	0.18 - 0.23	0.196
Si	0.15 - 0.35	0.236
Mn	0.30 - 0.60	0.44
P	$\leq$ 0.040	0.0030
S	$\leq$ 0.050	0.0020

Table 3. Physical Properties, ASTM A29.

Properties	Values	Units
Tensile strength	420	Mpa
Yield strength	350	Mpa
Modulus of elasticity	205	Gpa
Shear modulus	80	Gpa
Density	7.87	g/cm^3

AISI 1020 Steel has a high machinability, excellent strength, high ductility, and good weldability [5]. It's most commonly used in turned and polished or cold-drawn forms because of its low carbon content; it is resistant to induction and flame hardening.

3. Experimental work

Quenching is most frequently used in metallurgy to harden steel by producing a martensite transition, which requires rapid cooling through the steel's eutectoid point, which is the temperature at which austenite becomes unstable [10].

At beginning, the samples have been placed in a furnace set to 850°C for a period of 30 minutes and then quenched in oil by lowered the specimens in an oil-filled tank. Groups B, C, and D were treated in this trial, where Group A was left untreated. The samples (groups B, C, and D) following the quenching process are shown in Fig. 2.

Fig. 2 illustrates the samples after quenching.

The samples were then placed in the furnace for tempering at a temperature of 400 °C after the quenching process was completed for all three groups. The samples in group B were maintained in the furnace for 2 hours, after which the furnace switched off and the samples were kept inside until cooled, after which the samples were extracted. The same methods are followed for the remaining groups, but the samples are left in the furnace for different periods of time, such as group C, which was left in the oven for 3 hours while group D was left in the furnace for 4 hours. Torsional fatigue tests are carried out on groups A, B, D, and C, where group A being the original condition and the other groups being heat treated. The goal of the torsional fatigue testing was to observe and compare the AISI 1020 behavior.

The hardness of the heat-treated specimens has been calculated from the equations below [10].

$$Hardness = 0.5\left\{\left(1542.9 - \frac{25.3}{X_C}\right) \times \left(Exp\left(-1.8 \times 10^{-4} \times TF1\right) + Exp\left(-1.8 \times 10^{-4} \times TF2\right)\right)\right\} + 246.65\ log_e(T) - 1530 \quad (1)$$

$$TF1 = T\left(log_e(t) + 10.3\right) \quad (2)$$

$$TF2 = T\left(log_e(t) + \left(H_o + \sum_i H_i\, X_i\right)\right) \quad (3)$$

Where *Hi* is the alloying element constant, *Xi* and *Xc* are the mass percent of alloying element, and *Ho* is the tempered pure iron constant. *TF* is the tempering factor. *T* is the temperature of tempering and t is the time period for tempering process.

4. Results and Discussion

The investigation used a strain-based approach, in which the maximum and lowest shear strains for the materials were determined. Because it was based on strain, the behavior can be found for low cycles and then extended to a high cycle region. The approach for determining the behavior was to choose a shear strain and apply it to a specimen that would fail after several cycles. For the specimens of groups, record the number of cycles again, but with a different shear strain. The *S-N* curves for groups A, B, C, and D are shown in Fig. 3. The life-strain relationship is given by [10]:

$$\gamma_a = \left(\frac{1}{G}\right) \times \tau'_f (2N_f)^{bo} + \gamma'_f (2N_f)^{co} = \gamma_{ea} + \gamma_{pa} \quad (4)$$

Where the intercept and slope of the best-line fit to the surface shear stress amplitude τ_a, against failure reversals $2N_f$, data in log–log scale are shear fatigue strength coefficient τ'_f, and shear fatigue strength exponent *bo*. Similarly, the intercept and slope of the best-line fit to the plastic shear strain amplitude γ_{pa}, versus reversals to failure are shear fatigue ductility coefficient γ'_f, and shear fatigue ductility exponent *co*, data on a logarithmic scale, see Fig. 4.

Table 4 shows the fatigue coefficients for each group. The metals are heated to specific temperatures (850 °C) depending on their carbon content, and then swiftly cooled, usually by quenching in oil. The metals are heated to these temperatures, known as their (austenitic crystal phase), because their crystal structures can begin to alter, creating bonds to produce cementite as the carbon diffuses, which is a very hard, abrasion-resistant substance.

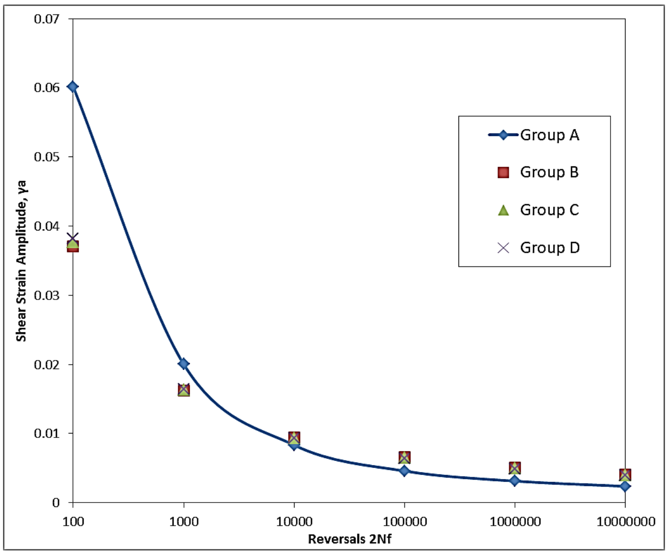


Fig. 3 Experimental torsional fatigue data for groups A, B, C, and D.

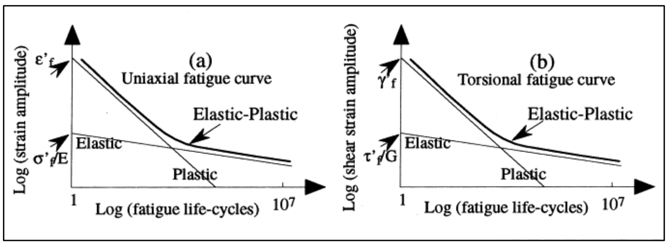


Fig. 4 Estimation of fatigue coefficients.

Figure 3 shows the fatigue behavior for heat treated and untreated of AISI 1020 which classified as groups A, B, C, and D. Figure 3 demonstrates that the heat treatment had a large effect on the plastic region of the fatigue behavior, but only a minor effect on the elastic region. This behavior happened due to the heat treatment had changed the fatigue coefficients in values, Table 4. Furthermore, the mechanical steel characteristics discovered to be highly sensitive to tempering time [11]. The changed in the fatigue behavior for all groups been discussed after all fatigue coefficients values estimated by applying the procedures as in Fig. 4. Tempering process was significantly improved the hardness and the mechanical properties this is due to phase change from ferrite-pearlite to martensite, retained austenite and low fraction of bainite [12].

Table 4 shows that the shear fatigue ductility coefficient γ'_f, decreased when comparing group, A with groups B, C, and D. Also, it can be observed the hardness has a reversal relationship with γ'_f. As a result, it can be concluded that heat treatment increased the hardness and decreased the shear fatigue ductility coefficient which lead to reduce the design region of cycles to failure in plastic region.

The shear fatigue strength coefficient τ'_f, was improves after the heat treatment process and had a significant impact on the elastic part's fatigue behavior, as compared to group A and other groups. This improvement leads to enhance the design region of cycles to failure in elastic region.

Table 4. Fatigue coefficients for AISI 1020.

Case	Hardness HB	Shear fatigue strength coefficient	Shear fatigue ductility coefficient	Shear fatigue strength exponent	Shear fatigue ductility exponent	Conditions
Group A	198.5	834.863	1.043	- 0.09	- 0.56	As received
Group B	382.57	1446.037	0.502	- 0.09	- 0.56	Q.T. 2 hrs
Group C	375.96	1424.085	0.518	- 0.09	- 0.56	Q.T. 3 hrs
Group D	371.35	1408.791	0.529	- 0.09	- 0.56	Q.T. 4 hrs

Carbon diffusion from martensite to other phases was caused by the tempering process. As a result of the longer tempering time, the carbon diffusion time was extended, the retained austenite was stabilized, and the volume percentage of bainite was marginally improved. Figure 5 depicts the effect of tempering time period on fatigue coefficients. The tempering time has an impact on the fatigue behavior of both plastic and elastic sections. It was found that increasing the tempering time produced decreased the shear fatigue strength coefficient while increased the shear fatigue ductility coefficient. This transformation caused reduction in hardness value [11].

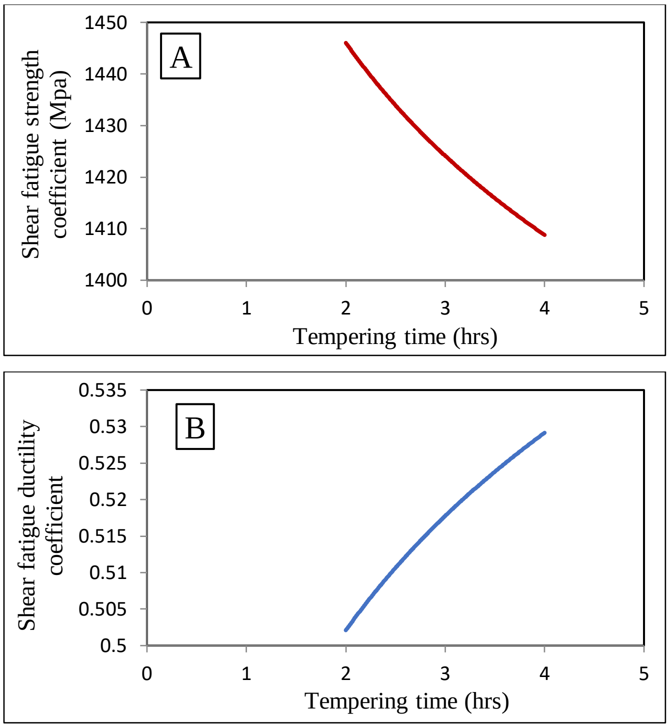
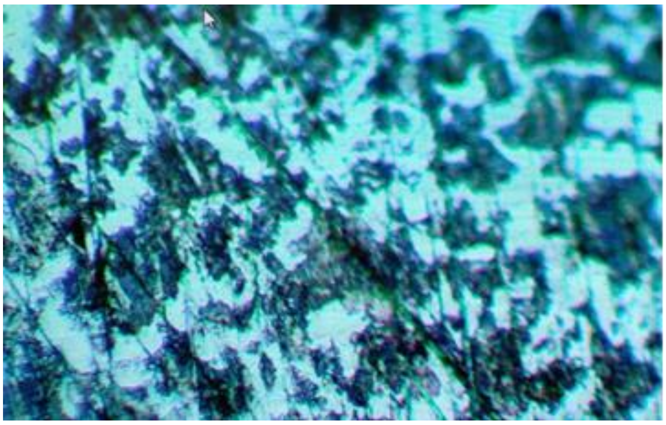


Fig. 5 Change of the shear fatigue coefficients with the tempering time.

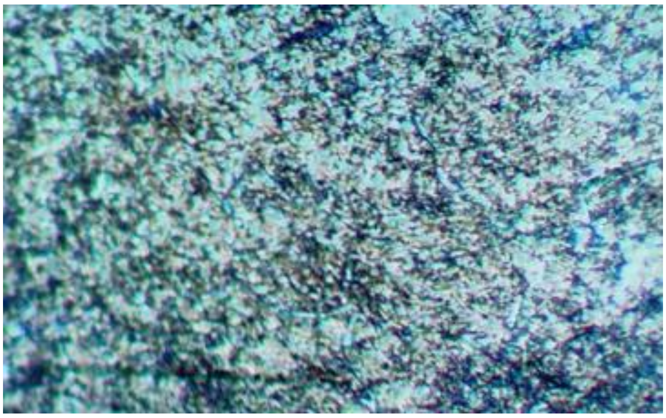
All of the specimens that had undergone various heat treatment techniques were subjected to an analysis using an optical microscope. The other goal of the study was to look at how heat treatment affected the microstructure of diverse materials. The microstructure of the receiving sample was first examined, and it was used as a baseline for all subsequent samples. All of the samples under investigation were polished. An etchant for AISI 1020 steel was made with reagent. Prior to microscopic examination, acid was administered to the polished surfaces of the samples for several minutes. Every sample was examined at a magnification of 70 x. The samples and their microscopic images are shown in Fig. 6.

The resulting microstructure is called pearlite when the sample is heated in the austenitic region and then cooled below a lower critical temperature. Pearlite is a ferrite and cementite lamellar structure. All of the microstructures depicted in Fig. 6 have a mixture of bright and dark sections. Due to the presence of cementite, dark areas are available. Pearlite is formed when cementite is combined with ferrite structure. The dispersion of cementite phase across ferrite phase varies with cooling rate. The microstructure of the received sample is used as a reference for other heat-treated samples in Fig. 6 (a). The pearlite structure in the steel samples could be seen clearly in the black circular area and the rounded rectangular part. Despite the fact that the lamellar structure could not be reported in this study, considerable disparities in microstructural sizes were identified in all samples.

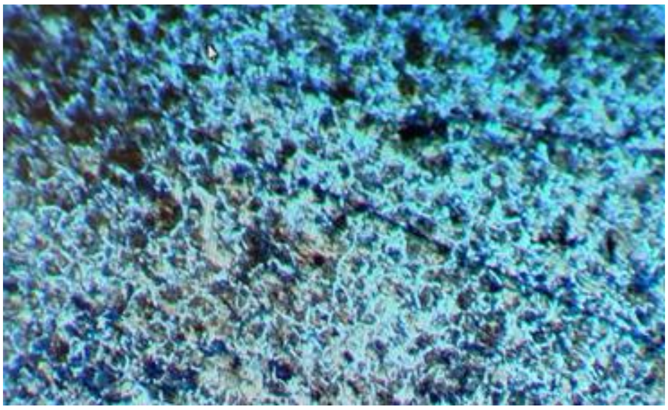
It is extremely difficult to distinguish cementite precipitates from α-ferrite during the oil quenching process. The creation of lamellar structure is usually prevented by this rapid cooling rate, resulting in a thin or needle-like structure seen in microscopic images. Because oil quenching phenomena often give a high cooling rate, the final structure contains very fine pearlite and also unstable austenite [12].



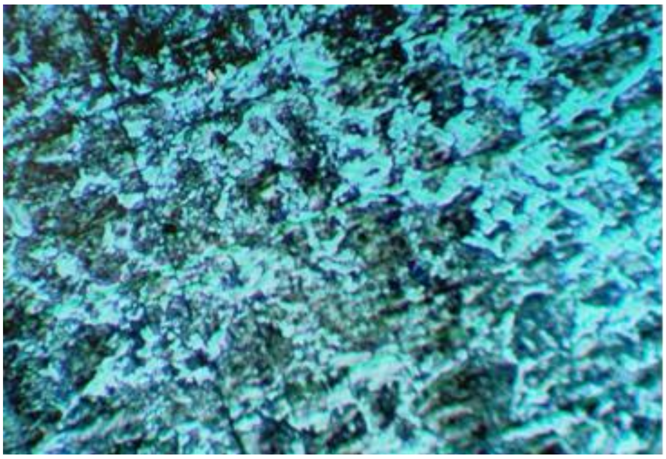
(a) As received sample group A.



(b) Quenching and tempering for 2 hrs, group B.



(c) Quenching and tempering for 3 hrs, group C.



(d) Quenching and tempering for 4 hrs, group D.

Fig. 6 Microscopic images for groups A, B, C, and D.

5. Conclusions

This research is based on the examination of hardened medium alloy steel solid specimens that were subjected to cyclic torsion deformation and fatigue tests with constant amplitude. The following conclusions are conceivable to illustrate:

1. Heat treatment improved hardness and the shear fatigue strength coefficients while lowering the shear fatigue ductility coefficient. This variation leads to reduce the design region of cycles to failure in plastic region and enhanced in the elastic region.
2. Heat treatment improved the shear fatigue strength coefficient, which had a substantial impact on fatigue behavior.
3. The period of tempering time has impact on fatigue coefficients. It was found increasing the tempering time will decrease the shear fatigue strength and, on the hand, will increase the shear fatigue ductility coefficients.
4. Optical microscope was used to examine the microstructures of all of the samples. The impact of cooling rate on microstructural sizes was the focus of the research. There was a strong precipitation of cementite over ferrite in the oil quenched sample, which indicated an extremely fine microstructure. A fine microstructure, according to the study, gives high shear strength, ultimate tensile strength, and hardness, but at the expense of ductility.

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