THE EFFECT OF PACK CARBURIZING ON HARDNESS AND FATIGUE STRENGTH OF LOW CARBON STEEL

Muamar M. Ben Isa*, Hitem A. Aswihli, Abdusalam M. Sharf

Mechanical and Industrial Engineering Department, Faculty of Engineering, Al-Asmarya Islamic University, Zliten, Libya.
* Corresponding author: m.benisa@asmarya.edu.ly

ABSTRACT

For many engineering components such as gears, shafts and valves, it is an advantage to use steel (iron) with a hard surface (case) and a soft, tough interior (core). This is usually achieved by one of several case hardening treatments, in which, the surface layer of the soft steel enriched with hardening alloying, usually carbon, by diffusion treatment. The main purpose of this work is to study the pack carburizing of the low carbon steel by means of three different holding times which are; 4, 6 and 8 hours at a temperature of 925°C. Also in this paper, fatigue strength was examined for different samples under certain conditions. The combination of the carburizing mixture (carburizer) used in this study was 87.5% charcoal and 12.5% barium carbonates (carefully mixed). From the experiments, the hardness gradient and the thickness of carbon layer were highly effected by the duration of the carburizing process. The hardness range through the carburized case could be tightly correlated with the carbon content of martensite. The highest hardness value and carbon gradient recorded (layer thickness) were after carburizing treatment for eight hours. Water was used as the quenching medium in the quenching experiments. Some of the tested specimens were exposed to a tempering treatment at 200°C and 450°C for three different times i.e. $1/2$, 1 and 1 $1/2$ hours. The highest hardness value achieved was after tempering at 200°C for $1/2$ hour, while the lowest value was at 450°C for 1 $1/2$ hours. Mean while, the highest fatigue strength value was monitored after tempering the carburized samples.

Keywords:*Pack carburizing, hardness, carbon gradient and fatigue strength.*

1. INTRODUCTION

Carburizing is a heat treatment in which, the specific carbon content at the surface of low carbon steel, is increased by the exposure to an appropriate atmosphere at a specific temperature in the austenite phase field. In carburizing,in order to produce a carburized layer by diffusion, steel is heated up for a certaintime (hours) at high temperatures, about 900°C (between 850°C to 950°C) in carbon-rich atmosphere provided by gaseous,

liquid or solid carbon aceous substance [1,2]. Theoretically, the surface layer of the metal could attain a carbon content determined by; the carbon potential of the surrounding environmentand the carburizing temperature,taking into account not exceeding the solubility limit of carbon in the metal (A_{cm}line). However, if the chemical balance in the environment yields a carbon potential of 0.8%, that carbon content will not be exceeded regardless the carburizing temperature. In most instances, carbon potential of the environment would be controlled to achieve the desired carbon content at the surface of the metal. The chief benefit of using high temperatures, above 815˚C, for carburizing is that to increase the absorption and diffusion rates, which reduces processing time [2, 3].

Carbon concentration gradient of the carburizedcomponents is influenced by carburizing temperature, time, type of cycle (various combinations of carburizing and diffusion), carbon potential in the furnace and the original combination of the steel [5]. Generally, the carbon concentration gradient developed during carburizing depends on the following factors: (i) the carbon potential of furnace atmosphere; the higher potential the fasterthe carbon is supplied to the steel and steeper the carbon concentration gradient at the steel surface (ii) Carburizing time; the depth of the carbon content increases as the process time increases (iii) Alloy content of the steel exerts its primary influence on the case carbon content together with the surrounding on the diffusion rate (iv) The increase of the carburizing temperature results in increasing the reaction rate on the steel surface[2,3 and 5]. Many researchers were connected to case hardening of steel. Mohamed[6] investigated the mechanical properties of pack carburization of low carbon steel AISI 1010 rod which was processed at (850, 900 and

950˚C),using granules of carbon powder of (cook +CaCO$_3$) as a carburizer.The study concluded that the mechanical properties such as hardness and wear resistance of low carbon steel were strongly influenced by the carburization process. As the carburizing temperature increases the hardness and wear resistance increases, where the highest value of hardness was achieved after carburizing at 950˚C with remaining a tough core. Oyetunji et al.[7] used palm kernel shell, animals bone, and seashell as carburizers in pack carburization of mild steel rod at temperatures range(700-1100˚C).They reported that, carbon content in solid solutions increases as the carburizing temperature increases from 800˚C to1100˚C. They also stated that palm kernel shell and animals bone carburizers have a good potential to be used as a carburizer for mild steel, while seashell has decline propensity to be used as a carburizer. Moreover, the hardness of the un-tempered samples carburized in palm kernel shell and animal bones showed higher values than the tempered samples. In Paul Ihom et al [8] study, various carburizing compounds were used for pack carburizing of mild steel. Different weight percentagesof cow bones were used as energizer in carburizing compounds. The experimental work was carried out at 900˚C for 8hours. They achieved2.32 mm as an effective case depth produced in steel carburizing by using 60wt.% charcoal and 40 wt.% cow bone with the highest hardness amongst the results using the other compositions(i.e. 100wt.% charcoal, 70wt.% charcoal and 30wt.% cow bone, 75wt.% charcoal and 25wt.% cow bone). Aramidr et al.[9] investigated the use of activated charcoal as a carburizer to improve the mechanical properties of the mild steel. They reported that the optimal mechanical properties were obtained at a temperature of900˚C. Alagble [10] reported that palm shell can be used in improving the hardness in mild steel over charcoal and graphite.

In Ihom et al.study [11], authors used the waste egg shells as energizer in the carburizing of mild steel, they obtained a case depth of 0.71mm after 3 hours duration of pack carburizing.Nukman and Chandre[12] used the charred goat bone and coconut shell as an energizer for carburizing mild steel. Authors reported that, tensile strength and impact energy were reduced by carburization by usingthese two materials as energizer in carburized mild steel, in a way much better than using the goat bone only.However,authors reported that, nearly 50% of the improvement in the hardness occurred when using the goat bone energizer and only 13% in the case of using coconut shell energizer.

The aim of this work is to study the pack carburizing of low carbon steel and its effect on the hardness and the fatigue strength. Also investigating the effect of the heat treatments such as; quenching and tempering of the carburized layer on the previous mechanical properties and the influence of the carburizing time on the carbon concentration gradients. The chemical heat treatment was applied on a 13 mm-diameter sample made of a low carbon steel containing, approximately0.2% C.

2. EXPERIMENTAL PROCEDURE

Low carbon steel (0.2%C) specimens were prepared as pieces of 15mm in lengthand 13mm in diameters for carbon concentration and hardness measurements. Table 1 shows thechemical composition of the used material.

TABLE 1: THE CHEMICAL COMPOSITION OF THE USED MATERIAL:

| Component	C	Mn	Si	K	P	Ni	Al
Wt. Percentage%	0.2	0.61	0.18	0.01	0.063	0.098	0.01

In the beginning, all samples were cleaned with distilled water. The carburizing mixture was mixed and prepared carefully (charcoal and barium carbonates). The samples were completely surrounded by a 25 mm-layer of the mixed carburizing mixture (energizer), and then pressed in a mild steel box. The distance between any two rows of samples, and between the samples and box walls were 25mm, and so on up to the last mixture layer of thickness which was about 35 to 40 mm in order to condensatethe loss contraction which could occur. To prevent oxygen from entering inside the box, the clearance between the box and its cover was filled with clay. Afterwards, the box was placed inside the furnace at a temperature of 925˚C. The carburizing time considered to be started when the furnace temperature reaches 925˚C. After a required certain time, the furnace was turned off and the box left to be cooled down to the room temperature. The carburizing experiments were approached at three different times; 4, 6 and 8 hours. Four specimens were picked up, one was as the received sample (before carburizing) and the other three were from the carburized ones at the three different carburizing times (duration) and then prepared for the carbon concentration and hardness tests. The next stage was the heat treatment of the remained carburized samples at 870˚C for 45 minutes. After that, samples were picked up from the furnace and directly quenched in water. One sample was dried and prepared for the carbon concentration and hardness measurements. The remained samples were dividedinto two sets, the first set was tempered at 450˚C and the second one at 200˚C, in both sets, three groups were heated, the first group tempered for ½ an hour, the second for an hour and the third one for 1½ hours. All samples were cooled down in air. All tempered specimens were prepared for hardness measurement as previous.

3. RESULT AND DISCUSSION

Pack carburizing is a process aims to saturate the low carbon steel surface with carbon in order to get harder surfaces and more sufficient wear resistance. That could be achieved by rising the carbon content at the surface from 0.2% C to (0.8-1.2)%C. The reason of the high carbon content which occurs on the surface after carburizing is that; at high temperatures (925˚C) carbon atoms diffuse through the iron matrix and become a part of the steel content. When carbon concentration reaches to the austenite saturation limit, a complete layer of cementite might be produced on the surface. Carbon concentration could be determined by the line (SE) on the iron-carbon diagram. Carburized layer usually would be formed at carburizing temperature from cementite. Yet, after annealing it forms ferrite and cementite [1]. Carbon concentration is a function of thickness, where the concentration decreases from the surface to the core. Figure 1 illustrates the effect of the carburizing time on the layer thickness, where the layer thickness increases by the increase of the carburizing time at a certain carburizing temperature (925˚C).As mentioned above, case depth is a function of the carburizing time i.e. increasing the carburizing time increases the case depth at a constant temperature and carbon potential and vice versa.It is clear that longer carburizing times give higher case depths which are shown in figures (1 & 2).Figure (2), illustrates the actual duration time of carburizing against the case depth at 925˚C. In this study, three different carburizing times were applied at a constant temperature (925˚C) and a constant potential.
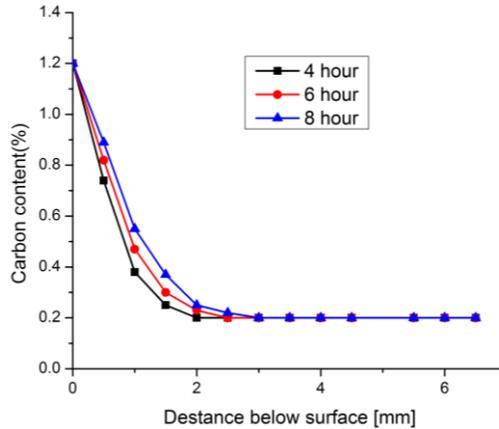
Figure 1: Carbon concentration after carburizing at 925°C for three different carburizing times
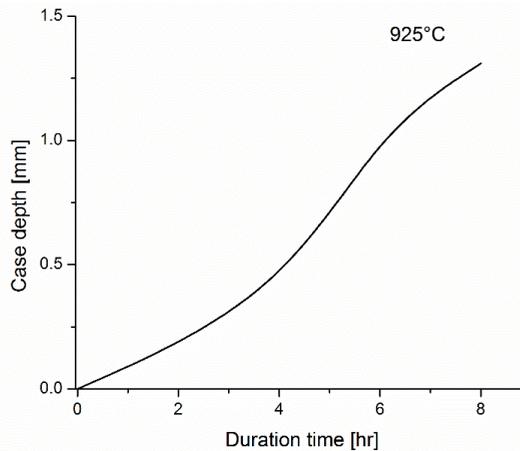
Figure 2: case depth vs. duration at 925°C

It is well known that, carbon concentration could be divided into three locations,(i) hypereutectoid region: which is formed from pearlite and cementite network,(ii) Eutectoid: formed from pearlite only,(iii) hypo-eutectoid: formed from pearlite and ferrite. The actual depth of the carburized layer could be determined even by taking the sum of the three locations depth (hypereutectoid,eutectoid and half of depth of hypo-eutectoid region), orit could be considered by the distance from the beginningof the surface until a point in which hardness is 50HRC(75.9

HRA)[3] as shown in figure(3). In this study, the active case depth was measured based on the hardness value (75.9 HRA) and found to be 0.36 mm for 4 hours, 1.045 mm for 6 hours and 1.31 mm for 8 hours.
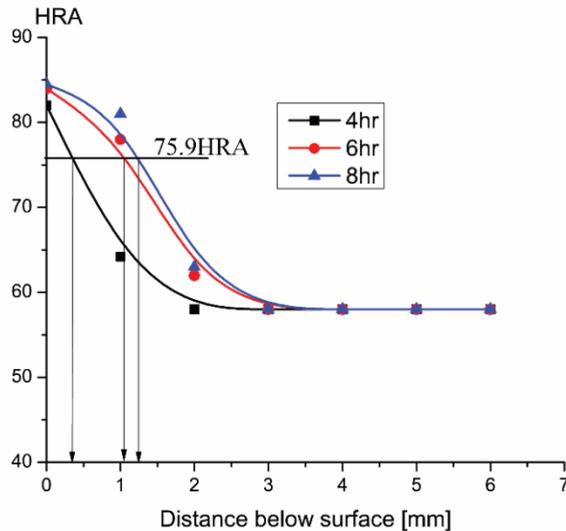
Figure 3: Schematic diagram showing hardness profile ofcase hardening of steel

As a result of carburizing process, pearlite in big grain sizes is produced with low ductility (brittle),for this reason water quenching was applied to decrease the grain size and eliminate the cementite network. Water quenching leads to the evolution of martensite. Generally, heat treatment is applied to improve the mechanical properties of products, properties such as; hardness, fatigue strength, etc. The hardness of martensite increases directly by theincrease of the carbon content. Figure (4),shows that pearlite produced after carburizing has a lower value of hardness when compared with the martensite produced by water quenching (the comparison between the curves that were treated at the same carburizing time).Increasing carburizing time leads to increasing the carbon content. Hence, the hardness

increases.Hardness value at 8 hours is higher than its value at 6 hours, and at 4 hours is less than the hardness at 6 and 8 hoursas shown in the figure (4). In addition, Fig. 4 indicates that hardness as carburizing and quenching after 6 and 8 hours have almost the same values which are higher than the hardness of 4 hours. This might be a result of the fact that; after 6 hours carbon content starts reaching the saturation case in the carbon steel.
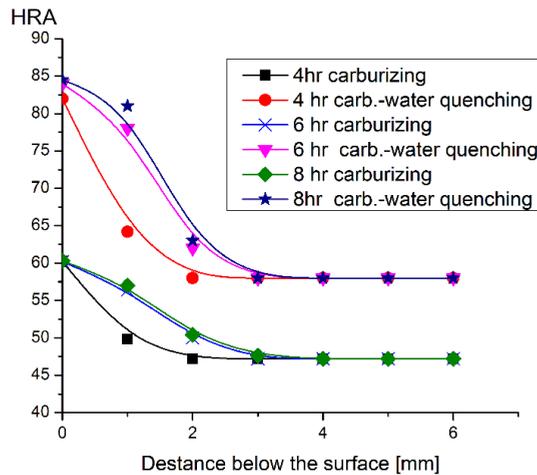
**Figure 4: Hardness values (HRA) after carburizing at925˚C
and water quenching for three different times**

Generally speaking, hardness achieved by water quenching has higher values when compared with those achieved at the same carburizing time.This is due to the fact that; martensite has a very low ductility and internal stresses (internal stresses which produced as a result of shear transformation and the change in the specific volume when γ phasechanges to α phase). Therefore tempering must be proceeded after quenching in order to release the internal stresses and increase ductility. Nonetheless, internal stresses could be released more efficiently by increasing tempering time and temperature besides decreasing the cooling rate. A result of tempering process, the fine grains will be produced [3]. Hardness decreases

with the increase of the tempering time and temperature as shown in figures (5), (6) and (7). Tempering temperature has the higher influence on hardness more than the tempering time, because it (the temperature) gives the carbon content the sufficient energy to be continuously decreased from the martensite [4]. The 4-hour carburized and quenched samples suffered a hardness drop after being tempered at 450˚C (for 0.5, 1 and 1.5 hours) when compared with the same samples tempered at 200˚C for the same durationsas shown in figures (5). This hardness drop is considered to be unusual when it is compared with the graphs in figures (6) and (7). According to Romesh [13], the reason stands behind that is 'when the martensite is tempered higher than 200˚C the cementite precipitates form and grow with time, with simultaneous dissolution of ε-carbide precipitates'. As the cementite precipitates grows, the carbon content in martensitedecreases. At the same time, the tetragonality of martensite will be lost and the c/a ratio becomes one (changes into a cubic lattice). When the tempering temperature increases (more than 250˚C), the equilibrium amount of cementite precipitate takes a short period. This could be explained by the phenomena of the lower hardness of the quenched 4-hour carburized samples after tempered at 450˚C, which occurred due to the fact that: carbon content has less time to be diffused when compared with the 6 and 8-hour quenched samples. Hence,low amount of martensite will be formed (faster cementite precipitation).Moreover, further studies should be carried out in investigating this particular phenomena at the different carburizing temperatures and times.
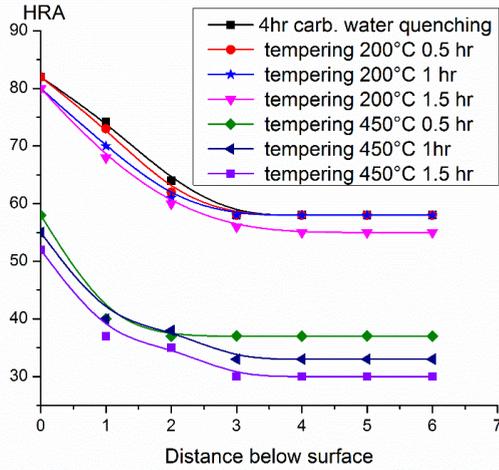
Figure 5: Hardness values (HRA) after 4 hours carburizing at 925°C, water quenching and tempering at 200°C and 450°C
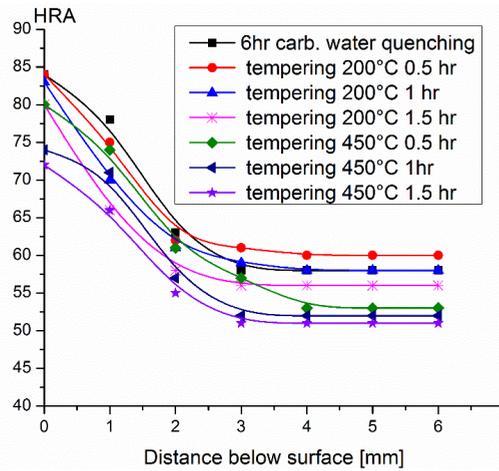

Figure 6: Hardness values (HRA) after 6 hours carburizing at 925°C, water quenching and tempering at 200°C and 450°C
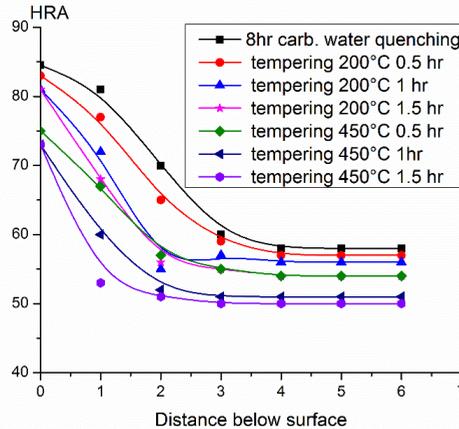
**Figure 7: Hardness values (HRA) after 8 hours carburizing at 925˚C,
water quenching and tempering at 200˚C and 450˚C**

4. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL EFFECT OF CARBURIZING ON CARBON CONTENT

To calculate the carbon concentration at the surface at a certain carburizing time, the following equation, called the solution of Flick's second low[2] could be used:

$$\frac{C - C_0}{C_1 - C_0} = 1 - erf \; \frac{x}{2\sqrt{Dt}} \qquad (3)$$

$$D = D_0 e^{\frac{-Q}{RT}} \qquad (4)$$

Where: C is the required carbon concentration at a depth (x) below the surface, C_0:the basic carbon content of steel $= 0.2$, C_1: the carbon content at the surface of the steel $= 1.2$, x: the depth below the surface (cm), D:the diffusion coefficient (cm^2/s), t: time(s), erf: the so-called error function, $D_0 = 0.25$ cm^2/s, Q $= 34.5$ cal/mol, T: the carburizing temperature $=1198$ºK, R: constant $= 1.987$. The carbon content and carbon concentration measured

considering the maximum carbon percentageat the specimen's surface which is equal to 1.2%C.

In this study, each carburizing time related to the carbon percentage versus the layer depth has been drawn, experimentally and theoretically. The experimental curve drawn using experimental resultsobtained according to the hardness measurements, while the theoretical curve drawn based onvalues obtained from equation (3) and shown in figures (8), (9) and (10). The experimental and theoretical results showed a perfect match, which makes it a worthy procedurein calculating the case depth, illustrated in figures (8), (9) and (10).
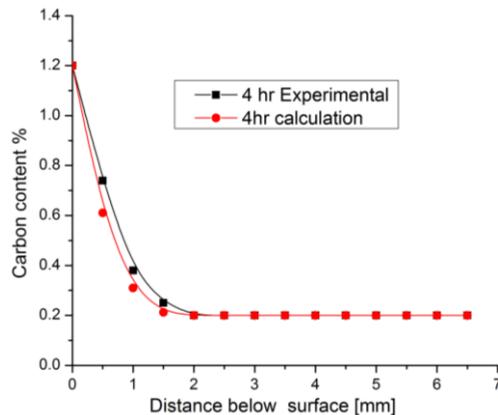
Figure 8: Theoretical and experimental carbon content as a function of the case depth for 4 hours carburizing at 925°C
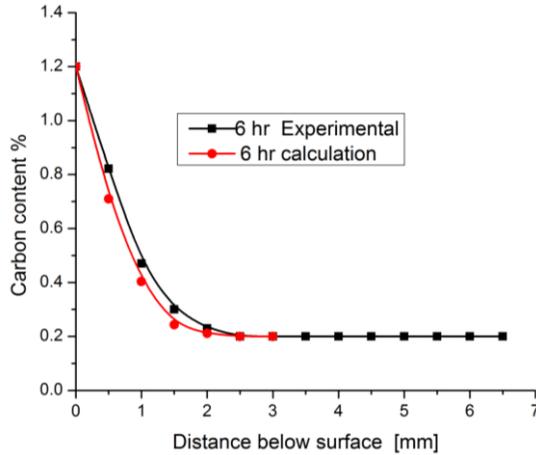
Figure 9: Theoretical and experimental carbon content as a function of the case depth for 6 hourscarburizing at 925˚C
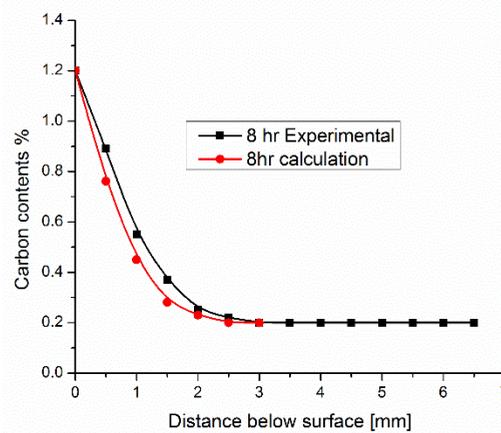
Figure 10: Theoretical and experimental carbon content as a function of the case depth for 8 hours carburizing at 925˚C

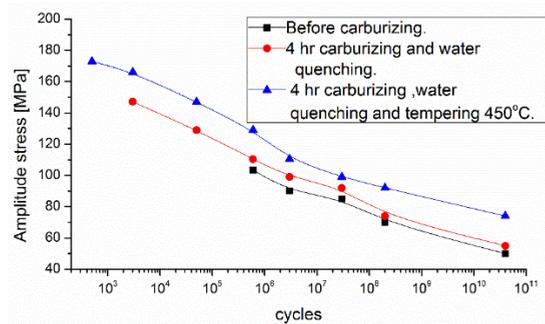# 5. EFFECT OF CARBURIZING ON FATIGUE STRENGTH

For the fatigue test, identical samples were prepared and exposed to annealing process at 870˚C for 45 minutes in order to release any residual stresses. Part of these samples exposed to a 4 hour-pack carburizing and water quenching processes. Half of the carburized samples were tempered at 450˚C for an hour. The non-carburized samples underwent a fatigue test

until fracture using a certain weight for each sample (w), the number of cycles (N) then were registered. Fatigue test have been approached for both, the quenched and the tempered sample. It is worthy to mention that, each specimen was rotated continually around its longitudinal axis while carrying the weight, which leads to subjecting the specimen to alternative bending moments. The applied weight starts from the highest value and decreases gradually.

Fatigue is the progressive localized permanent structural changes that occurs in a material subjected to a repeated fluctuating strain at a stress having a maximum value less than the tensile strength of that material.

Fatigue fractures are the most common causes of failure in engineering components, which are resulted by the simultaneous action of a cycle stress, a tensile stress and a plastic strain. If any of these three reasons is not present, fatigue will not initiate and propagate. The cycle stress starts the crack which grows up and propagates by the tensile stress. The test specimen was already slightly waisted in the middle to prevent the fracture from developing at the loading or the supporting points. A smooth changing in the sample section was employed to avoid the stress concentration as possible. This action would certainly reduce the observed fatigue strength. The maximum stress at any section occurs at the specimen's surface and fluctuates around the zero line, (between the maximum tensile and compressive stresses). The stress amplitude (S) was plotted against the number of cycles until fracture (N), using the semi-log scaleas shown in figure (11).

Figure 11:Pack carburizing influence of low carbon steel on fatigue strength

The S-N curve indicates that, fatigue strength decreases with the increase of the number of cycles for the three specimen types. For the three types of specimens, the S-N curve approaches an infinite stress amplitude, which called the 'fatigue limit', below this limit; fracture will never develop leading to a great number of cycles. The data were plotted on a Log (N) scale to determine the fatigue limit. In steel, this limit could be noticed as a distinct knick in the curve around 10^7 cycles.The reason for the infinite fatigue limit in ferrous materials still not very clear yet, although it probably could be connected with the strain ageing effects. The ratio of the fatigue limit to the tensile strength for carbon steel materials is about 0.5 and for the high alloy steel is about 0.3 [4]. In this work, this ratio for the as machined specimens was 0.32, for the quenched samples was 0.46 and for the tempered ones was 0.48. The S-N diagram indicates that the chemical heat treated subjected to subsequent heat treatment increases the fatigue strength. From figure (11), fatigue strength at $N = 1 \times 10^4$ cycles rises from 99 MPa for the as machined specimens to 126.6 MPa for the quenched (carburized and quenched) and to 152.3 MPa for the tempered samples (carburized, quenched and tempered). Where at $N = 5 \times 10^3$ cycles, the fatigue strength rises from 90.63 MPa for the as machined specimens to 129 MPa for the quenched specimens and to 138.3 MPa for the tempered samples. However,

the fatigue limit in our case study has been improved from 86Mpa for the as received samples to 95MPa and 104.1MPa for the quenched and the tempered samples respectively. The reason for the fatigue strength rise by carburizing could be connected to one of the following reasons: (i). the surface condition; good surface conditions lead to reducing the unusual fatigue strength of steel, (ii). since carburizing raises the carbon content of the steel at the surface, which increases the tensile strength, quenching and tempering increase the fatigue strength as shown in figure (11), (iii). production of compressive surfaces; during quenching, surface always loses heat faster than the core (center) and undergoes the matrensitic transformation first. This leads to hardening the surface higher relatively to the center. As a result, volumetric changes will be produced in the phases leading to the presence of compressed surfaces and tensioned cores. It is clearly known that, fluctuating loads fracture occurs under tension, therefore the presence of the compression at the surface will make the fatigue fractures need more tension stress to happen than the normal surface.

6. CONCLUSION

In this study the pack carburizing of low carbon steel was studied using three different carburizing times 4,6 and 8 hours at a fixed carburizing temperature (925˚C). The carburizer (energizer) used in this work was component of 87.5% charcoal and 12.5% barium carbonates. From the obtainedresults, the following conclusions could be deducted:

1. Pack carburizing process increases the carbon content at the surface.Where carbon content increased from 0.2%C before carburizing to more than (0.8%C - 1.2%C) after carburizing.

2. Carburizing time increase leads to the increase of the carbon concentration gradient and the case depth of the high carbon surface layer.

3. The hardness of low carbon steel was found to be strongly affected by the pack carburizing process where it was improved from 47.2 HRA before carburizing to 60.3HRA after carburizing (by increasing carbon content). After water quenching of the carburized parts, the hardness increased to values up to 84HRAat the surface.

4. The hardness of the carburized parts was strongly affected by the tempering time and temperature, where the latter has more influenceon decreasing the hardness at the surface.

5. As the carburizing time decreases (4 hour in our case) the influence of tempering temperature was very evident to decrease the surface hardness.

6. Fatigue strength was improved by the pack carburizing heat treatment, where the fatigue strength has been improved, at certain number of cycle ($N = 10^4$ cycles), from 99MPa for the as received samples to be 126.6MPa for the quenched samples and 152,3MPa for the tempered ones. This improvement was for the fatigue limit as well.

In future studies, Authors aim to investigate the influence of the variation of the carburizing temperature with different carburizing times on the active case depth, and which factor has the highest impact.They alsointent to determine the optimum factors (such as; temperature, time and energizer)which lead to a certain case depth.

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