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# SURFACE HARDENING EFFECT ON THE FATIGUE BEHAVIOR OF ISOTROPIC BEAM

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Abstract

This paper is to present an experimental study of the impact of surface hardening on the high-cycle fatigue behavior of an isotropic beam. The beams made from low carbon steel (St 44-2). Surface treatments used are pack carburizing and carbonitriding. The experimental work included mechanical test, surface heat treatment, fatigue test and Microscopic inspection. The surface hardening was done by using pack-carburizing process at a temperature of 925°C holding time variation (2, 4, and 6hr) followed by quenching and tempering process, and using the carbonitriding process at a temperature of 800°C and for periods (0.5, 1 and 1.5hr) then quenching directly in water. The fatigue test was carried out by a cantilever rotating-bending system. The results of an experimental fatigue test indicate that various behaviors depend on surface heat treatment and time soaking. The findings indicate that carbonitriding has a greater impact on the fatigue strength and life than the specimen has been treated with pack carburizing. In addition, as the time soaking increase, the fatigue life will increase for both types of surface heat treatments. It was found that the specimens that were hardened using the carbonitriding process achieved a higher surface hardness as the hardness increased to 1644.62HV, while the untreated specimens were 293HV. Compared with the hardening using the pack carburizing process.

Keyword: fatigue behavior, carbonitriding, pack carburizing, S-N curve

**Nomenclature**

| | |
|---|---|
| SSP | Severe shot peening |
| LCS | Low carbon steel |
| HRB | Rockwell Hardness measured on the B scale |
| SPP | Stroke-peening process |
| SSP | Superimposed stroke peening |
| HCF | High-cycle fatigue |
| IHS | Induction-hardened surface |
| ZnO | Zinc oxide |
| HV | Vickers hardnes |

## 1. INTRODUCTION

With the advancement of technology, especially in the realm of industry, High dynamic loads are applied to an increasing number of structural sections and components, causing fatigue failure to occur [1]. Huang et al., [2] concluded that Fatigue failures commonly begin at the material's surface for two reason. Maximum stresses in these locations occur under most types of loading (bending and torsion) and focus of surface tension caused by surface finishing conditions or the presence of extrusion or intrusion materials. Fatigue is a slow-growing process that causes material's mechanical characteristics to deteriorate of one or more cracks that finally shatter as a result of dynamic loading. It is also considered one of the most catastrophic types of steel structural failure), and It can lead to huge casualties as well as financial loss. It is also considered a problem affect any moving part like ships, cars, fuselages, airplane wing, nuclear reactor, jet engine, and turbines are all subject to [3-5]. Gangaraj et al., [6] studied the impact of the combination of SSP and nitriding on the fatigue by using material low alloy steel. Comparing the samples that were received and the fatigue limit were experimentally. Rotating bending fatigue test used in this work. It was concluded that the use of nitrogen and severe shot peening improved the fatigue limit by 11.6% and 51.3% and Improve hardness and nitrogen diffusion. The mixing of nitriding and SSP increased the micro hardness. Abioye et al., [7] investigated the surface hardness of the carbonitrided (steel) in air, oil and brine quenching media. Conclude that cyaniding is an effective method of increasing the surface hardness of steels. In addition, the surface hardness of cyanide steels depends on the cooling rate experienced in the quenching medium with the brine producing the highest hardness at all temperatures. Within the heat treatment temperature range of 790°C to 920°C, the surface hardness of the steels increases with the rise in the temperature. The surface hardness of LCS increases with the heat treatment time. Carbonitriding is a surface hardening process of steel by heating on critical temperature, quench and followed by tempering process. Yudha et al., [8] studied the pack media in carbonitriding as a new method on low carbon steel with holding time variation. Temperature for pack carbonitriding was at and 800°C holding time variation 1hr and 2hr respectively. The result showed that carbonitriding temperature difference affect the mechanical properties of steel. Steel hardness was increased at lower holding time (1hr) compared to 2hr. The result showed that at 700°C and 750°C with 1hr variation, the steel hardness increase from 85.7 HRB to 95.7 HRB and at 800°C the hardness decrease to 93.1 HRB. Abdulraoof, [9] studied effect of hardening on hardening strength of medium carbon steel, the flame hardening method was used at different speeds then fatigue test was done. It has been found that as the flaming speed increases, the fatigue strength of the material decreases. Allaoui et al., [10] they investigated the impact of boriding treatment on the cyclic fatigue strength in solid media of C20 carbon steel. Showed that the improvement in fatigue resistance carried by the boriding treatment on C20 steel is low. Leitner et al., [11] they investigated how mechanical treatments such as induction hardening and SSP affected the fatigue and fracture behavior of gas engine (50CrMo4) steel crankshafts. Rotating bending fatigue tests show that the additional SPP raise the HCF strength of the IHS layer about 20%, which demonstrates the positive impact of the improved residual stress state.

Mohamed, [12] studied experimentally and numerical effect of nanomaterial coating type on the fatigue behavior for low carbon steel beam. ZnO, $Al2O_3$, and a combination of both are the nanomaterials that were utilised. The outcome of an experimental fatigue test demonstrates that variable behavior relies on the type of coating material and coating thickness, for all types of coating materials who it used, the fatigue life increased.

Diyar et al., [13] they studied the effect of the carburizing procedure on the mechanical properties of AISI 1011 low carbon steel. Noted that the hardness of this alloy increased to 431.65HV for samples carbonized at 950°C for five hours, compared to 169.65HV for untreated samples. For specimens treated with the carburizing procedure, the surface roughness of the metal increased. The results show that there is an increase in the wear rate with the increase in the applied load and the hardness decreases from the surface towards the core after the carbonization process. Carbonized samples have a higher wear resistance than untreated samples. Alza .,[14] research was done on how cyanide in a salt bath affected the wear and hardness of medium carbon steel. The results show that the hardness and wear characteristics of steel are enhanced to their ideal levels when cyanide is applied, if the cyanide treatment is performed at 850°C.

The aim of this research is to show the influence of surface heat treatments (pack carburizing and carbonitriding) on the fatigue life behavior of low carbon steel alloy beams under rotary bending loading of different time soaking, and also study the influence of surface heat treatments on the hardness.

## 2. EXPERIMENTAL WORK

### 2.1. Material Selection

Low carbon steel (st44-2) alloy was used for investigation in this work. The chemical composition of the selected material was done using the spectrometer device. Chemical composition (wt. %) is C: 0.22, Si: 0.136, Mn: 0.499, Cr: 0.138, Ni: 0.14, Fe: Ball.

### 2.2. Mechanical Test

#### 2.2.1. Tensile Test

The tensile test was performed using a universal testing machine type (WAW-200 – 180kN) at a speed rate of 2 mm/min, the ASTM-A 370 specification is followed in the manufacturing of the test specimens for tensile strength. (Gauge length (G) of 35 mm, diameter (D) of 8.75 mm, length of reduce section (A) is 45 mm and Radius of fillet (R) 6mm) [15] as shown in the Fig. 1. Table 1. Displays the findings from the tensile test of a sample of low carbon steel by the general testing machine, where the average value of three readings was recorded to achieve additional accuracy, the mechanical properties can be known as follows.

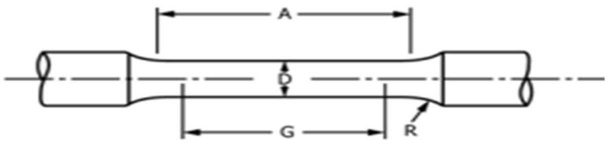


Fig. 1. Schematic of tensile test specimen according to the specification of (ASTM-A 370)

Table 1. Show the tensile test results of low carbon steel

| Property | Average Value |
|---|---|
| Yield Strength $\sigma y$ (MPa) | 385 |
| Tensile Strength (MPa) | 530 |
| Modula's of Elasticity E (GPa) | 202 |
| Percentage Elongation | 21 |

#### 2.2.2. Hardness Test

The hardness test of low carbon steel sample was tested by the Vickers method with the type of device (HVS-1000), of (100 g) applied load and during a period of time (10 sec) .Fig. 2. Shows the hardness sample and the locations for measuring the hardness of the metal before and after thermal treatments and knowing the solidification depth.

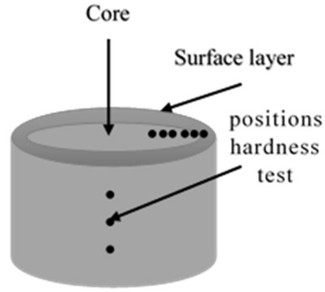


Fig. 2. Schematic for hardness sample

### 2.3. Surface Heat Treatments

#### 2.3.1. Specimen preparation

The ASTM standard (single cantilever rotational bending model) parameters were used to create the fatigue specimens in this study, by using (CNC) machine. Fatigue samples had been worked with dimensions that meet the device test standards for cylinder-shaped specimens, The dimensions of the cylindrical samples were free part (8 mm), fixed diameter (12 mm), and total sample length (146 mm) where the stator length is (40 mm) as shown Fig. 3. All fatigue specimens were manufactured notched specimens. The material used in this investigation are low carbon steel (st44-2). The notches is circumferential V shape notch of angle of (α= 45°) to a depth of notch was (h=1 mm) [16]. Fig. 4. Show the fatigue specimens with dimensions.

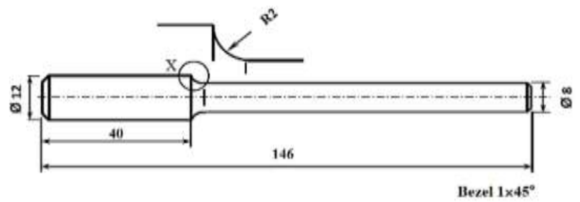


Fig. 3. Schematic diagram for fatigue test specimens

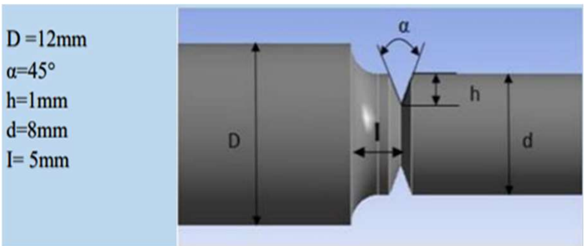


Fig. 4. Dimensions of V shape notch specimens

#### 2.3.2. Pack (sold) carburizing

It is the process of increasing the percentage of carbon in the surface. Carburizer media used is wood charcoal and Barium Carbonate ($BaCO_3$). 10% barium carbonate and 90% carbon powder were used and mixed together, placed into container (box) made from low carbon steel. Specimens and media carburizer (Powder carbon mixed with $BaCO_3$) are inserted into the carburizing box and closed tightly. Then heated specimens to a temperature of 925°C. At 925°C the specimens were held for (2, 4, 6) hr. The furnace was then turned off, allowing the temperature of the specimen to drop at the same pace as the furnace. Then they were quenched at a temperature of 850°C for 16 minute and followed by water-cooling [17]. The specimens have been heated at temperature 180°C and hold for 1 hr to remove internal stresses [18]. Look at the Fig. 5. Where it shows the work steps during the carbonization process.

#### 2.2.3. Carbonitrid (cyaniding)

A quick surface hard layer can be obtained on low carbon steels by cyanide. This process involves the introduction of both carbon and nitrogen. Sodium cyanide salt bath was used with the following composition (61% NACN +24% KCL + 15%$K_2CO_3$). The samples are placed inside the salt molten at a temperature of 800°C and the samples are kept inside the molten for periods of time (0.5, 1, and 1.5) hr. Then cool the samples directly in water flowed by tempering for 1hour at temperature 180°C. Fig. 6**.** Showing the cyanide process with time and temperature.

#### 2.3.4. Tempering

It is the process of heating a martensitic steel at a temperature below the eutectoid transformation temperature. This makes it "softer" and more ductile”. Tempering is applied to hardened steel to reduce brittleness. In this work used a temperature of 180°C for an hour gives a higher fatigue strength, due to the formation of the tempering martensite structure according to [17-18].

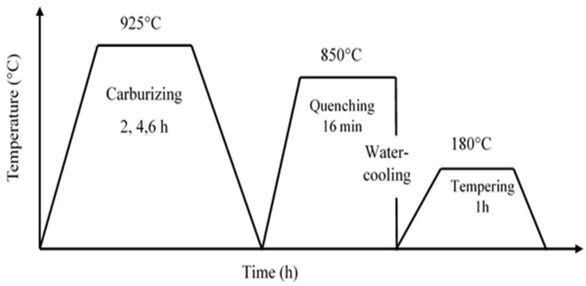


Fig. 5. Heat treatment (pack carburizing)

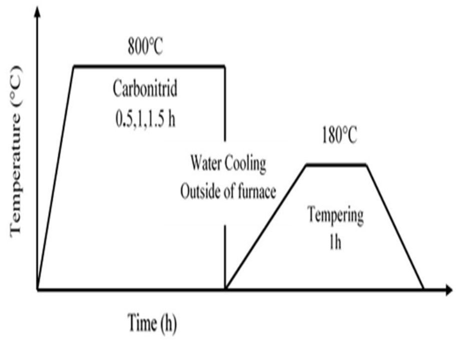


Fig. 6. Heat treatments (cyaniding) for low carbon steel

### 2.4. Fatigue Test

- Rotating bending fatigue

The fatigue-testing machine shown in fig. 7. Was designed with a (constant amplitude load) (fully reversed bending). The machine type is (WP 140) a single cantilever rotating bending. Rotating specimen is fixed and has a force applied to one side of it that has a maximum capacity of (0.5 kN) at a fixed frequency of (50Hz). A cyclic sinusoidal load is applied throughout the experiment with a stress ratio of R = -1 (minimum load / maximum load). For creating rotating bending fatigue conditions, the load to the opposing side must be applied. The shutdown sensor caused the machine to automatically stop once the specimen was broken. The number of cycles till failure is then calculated and displayed on the digital counter. Using the values of the bending moment, the alternating bending stress is determined, which may be calculated simply from equation (1). Several tests were conducted by representing a sample of the stress cycle and then the sample life (no. of cycles until failure) was calculated at variable surface treatment of testing space. The fatigue test procedure is repeated to the next. The samples are shown as tapering off the applied stress amplitude and S-N Curves are used to graphically display the recorded results. Tests were performed in the range of 160-420 MPa at peak alternating stresses, using a minimum of seven samples per test condition.

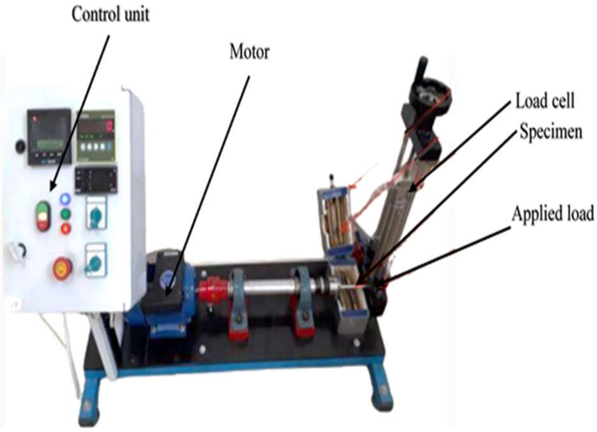


Fig. 7. Fatigue testing machine

Bending moment values can be calculated from equation [19]

$$\sigma_f = \frac{32F.L}{\pi d^3} \quad (1)$$

$$\sigma f \approx 2F \quad (2)$$

Where:
σf: Maximum alternating stress (MPa);
F: Applied load (N);
L: Bending arm = 106 ± 0.1 mm;
d: Diameter of the specimen = 8 ± 0.1 mm.

### 2.5. Microscopic Examination

Microscopic examination of the surface layer was carried out using a high-resolution optical microscope (Olympus BX60M) on cylindrical specimens with 12 mm diameter and 10 mm length [20]. It had been treated it by pack carburizing and carbonitriding In addition to the metal raw. Various grades of emery papers are used to grind the test piece's surface. After the test samples are polished with a rotary polishing machine with aid of diamond paste until a mirror-like surface is reached, the polished surfaces are etched by nitric acid (2%) and alcohol (98%).Finally, photographed by (G.K.B., CCD) camera attached to the microscope to know the microscopic structures resulting from the diffusion process. With magnification of 100X. Fig. 8. Show microstructure for material as received. It contains dark areas of perlite and light areas of ferrite. After pack carburizing (10 % $BaCO_3$) and 90% powder carbon) at 925°C with time 2 hour, at Fig. 9. It is noticed that pearlite increases on the surface and then gradually decreases towards the core as a result of the diffusion of carbon atoms resulting from the chemical reaction, forming iron carbide Fe3C, which is characterized by its high resistance to fracture [18]. As an energizer, 10% barium carbonate is added to the steel to speed up the diffusion of carbon, resulting in the formation of additional pearlite structures. Fig. 10 present microstructure of low carbon steel whose surface has been treated with carbonitrid. The white compound layer can be seen as a result of the diffusion of nitrogen and carbon together. As this reaction results in the diffusion of two carbon and nitrogen atoms together, forming iron carbide and iron nitride according to, which formed a high hardness of the metal [21].

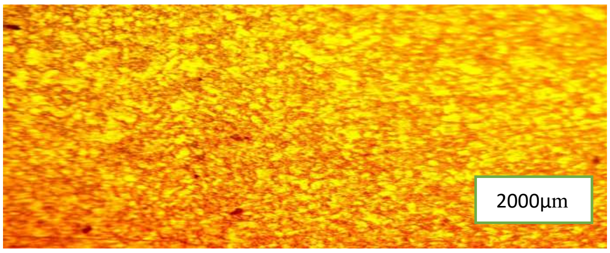


Fig. 8. Microstructure of material as received

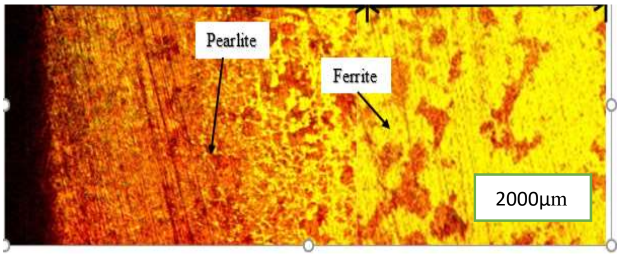


Fig. 9. Microstructure of carburized material

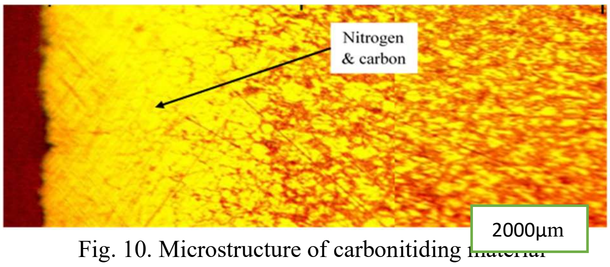


Fig. 10. Microstructure of carbonitiding material

## 3. RESULTS AND DISCUSSION

### 3.1. Hardness Test

Table 2 show the results of hardness test for metal low carbon steel after and before surface treatment, Fig. 11. It shows the relationship between surface hardness and immersion time for each hardening process. An increase in the surface hardness of both solid carbonization and carbonation is observed as a result of carbon diffusion in the surface, forming iron carbide during the carbonization process. As for the carbonate, carbon and nitrogen diffuse, forming iron nitride on the surface, at a certain depth towards the core. It was also found that the different time affect the hardness, the longer the soaking time, increased the surface hardness.

### 3.2. Fatigue Test

There are several factors affected on the fatigue performance. The effect of surface heat treatments, time soaking and notch is stated in this study. Where the

Table 2. Hardness test results of low carbon steel

| Material | T(hr) | No. specimens Vickers ,HV | | | Average Value |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| As received | - | 291 | 293 | 295 | 293 |
| carburizing | 2 | 992.21 | 996.1 | 997.51 | 995.27 |
| | 4 | 1027.9 | 1034.23 | 1039.65 | 1033.92 |
| | 6 | 1079.02 | 1083.87 | 1085.15 | 1082.68 |
| Carbonitriding | 0.5 | 1511 | 1529.33 | 1533.25 | 1524.52 |
| | 1 | 1543.34 | 1547.61 | 1551.11 | 1547.35 |
| | 1.5 | 1610.9 | 1655.7 | 1667.28 | 1644.62 |

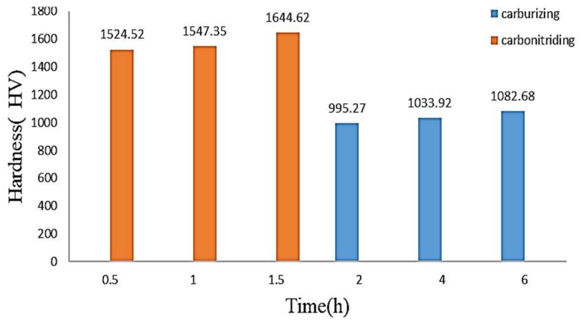


Fig. 11. Influence holding (soaking) time of carbonitriding and carburizing on hardness of low carbon steel specimens

notch is one of the factors affecting the fatigue life. Fatigue failure occurs mostly as a result of stress concentration in this area (v-notch). Therefore, surface heat treatments were performed of notched fatigue specimens. Fatigue tests were performed for both type of surface heat treatments are pack carburizing (P.C) and carbonitriding (C.N) at different time soaking tested. The cylindrical specimen under consideration is being subjected to bending stress due to vertical component force, so as the shaft rotates there is a fluctuation of stress.The results are graphically recorded in the form of S-N, curves. These curves are constructed by curve fitting of the experimental data of fatigue tests. Fig. 12. to Fig. 14 express the S–N (stress-number of cycles to failure) curves of the pack carbonization (P.C) at time (2, 4, and 6 hr) and carbonitriding (cyanide) at time (0.5, 1 and 1.5 hr). It can be seen that surface hardening by molten salt bath (carbonitriding (C.N) ) at temperature 800°C gives a greater improvement in fatigue performance compared to pack carburizing at temperature 925°C, this is due to the diffusion of nitrogen and carbon from the salt bath on the surface, forming iron carbide and iron nitride . Also, the diffusion velocity of the nitrogen atom is faster than that of the carbon atom, and it moves farther from the surface towards the core due to its small size, which causes a distortion of the crystal structure and an improvement in the mechanical properties. It was observed that the best improvement in the (S-N) curve was at a time of 1.5 hr during the cyanide process and also in the carbonation process at a time of 6 hr as shown in the Fig. 15.

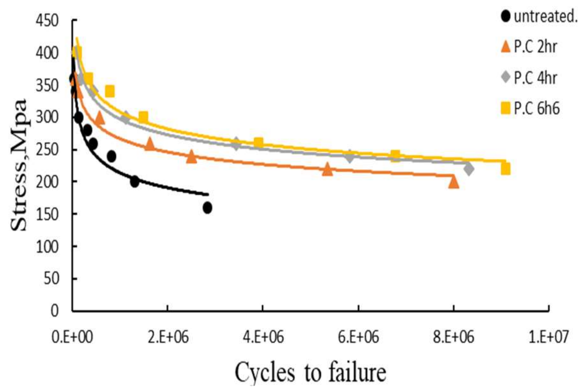


Fig. 12. Effect surface hardening (pack carburizing) on S-N curve of fatigue test specimens at varying time with un-treated

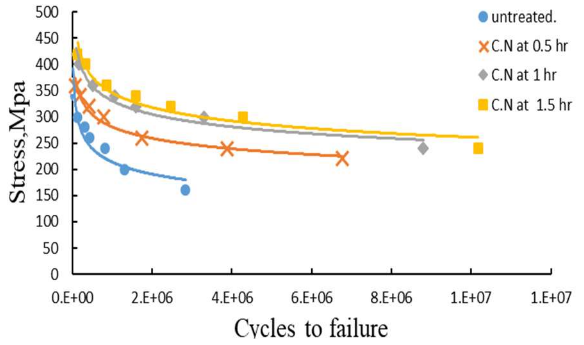


Fig. 13. Effect surface hardening (carbonitridng) on S-N curve of fatigue test specimens at varying time with un-treated

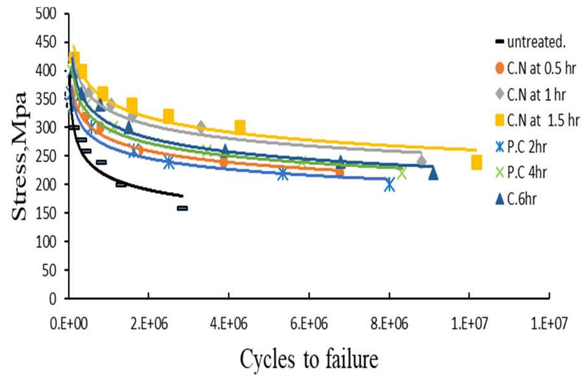


Fig. 14. Comparison between effect surface hardening (pack carburizing, carbonitriding) on S-N curve of fatigue test specimens at varying time with un-treated

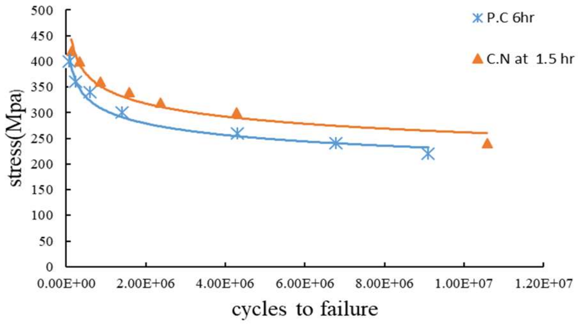


Fig. 15. Comparison S-N curve (carbonitrid at time 1.5h and pack carburizing at time 6h)

## 4. CONCLUSION

The study leads to the following conclusions:

1. Surface heat treatments by pack carburizing and carbonitriding improved fatigue life compared to untreated metal.The best improvement in fatigue life occurs with treatment with carbonitriding compared to the improvement achieved through carbonation.
2. The surface hardness increased with the increase in soaking time.
3. The greatest hardness value of 1644.62HV occurred at carbonitriding as a result of the diffusion of carbon and nitrogen atoms and the formation of cementite $Fe_3C$ and iron nitride $Fe_4N$.
4. endurance limit and fatigue strength increased after treatments

***Author contributions:*** *research concept and design, S.H.N.; Collection and/or assembly of data, S.H.N; Data analysis and interpretation, S.H.N.; Writing the article, S.H.N.; Critical revision of the article, Q.H.B.; Final approval of the article, Q.H.B.*

***Declaration of competing interest:*** *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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