



A Fatigue Strength Prediction Model for Surface Roughness and Nitriding Effectson SAE 1035 Steel

O.O Obiukwu *,O.M.I. Nwafor, B.Okafor, G.O.Osueke

Department of Mechanical Engineering, School Of Engineering and Engineering Technology, Federal University of Technology, Owerri, Imo State, Nigeria.

***Corresponding Author:** O.O Obiukwu, Department of Mechanical Engineering, School Of Engineering and Engineering Technology, Federal University of Technology, Owerri, Imo State, Nigeria.

Abstract: The effects of surface roughness and nitriding treatment on fatigue failure of SAE1035 steel were investigated. After nitriding heat treatments, the fatigue strength of the various specimen having different finishes further improved. For the three average surface roughness (Ra) considered, three equations which describe the S-N curves were established. The application of these equations to specimens tested under cumulative fatigue damage shows that the roughness parameter must not be ignored. Hence a model considering this parameter is formulated. From the model, the fatigue strength predictions were in good agreement with the experimental results.

Keywords: Fatigue strength prediction; surface roughness; SAE 1035 carbon steel; nitriding.

1. INTRODUCTION

Fatigue is an important parameter in studying the behaviour of materials subjected to constant and variable amplitude loading [1]. These material which are regularly subjected to cyclic loading are prone to fatigue damage, which often start at the surface due to localized stress concentrations caused by machining marks, exposed inclusions or the contrasting movement of dislocations. Fatigue prediction is an important way to improve service performance and control failure particularly where safety is paramount. Components of machines, vehicles and structures are frequently subjected to cyclic loads, which in some cases may lead to their failure due to fatigue [2]. According to Bannantine et al. [3] fatigue failure involves a multi-stage processes that begins with crack initiation, followed by a progressive crack growth across the part with continued cyclic loading, and finally the sudden fracture of the component or specimen. Crack initiation and propagation, in most cases, can be attributed to surface integrity produced by machining [4]. Fatemi and Yang [2] reported that there are three commonly recognized forms of fatigue namely; high cycle fatigue (HCF), low cycle fatigue (LCF) and thermal mechanical fatigue (TMF). The average surface roughness (Ra) value might vary from 0.2 microns for a good polish to 8 microns for a rough turned finish [5]. Fatigue cracks initiate predominantly at the free surface of a material, and the condition of the surface can be assumed to be critical with regard to fatigue crack initiation [6]. Since the surface finish of the materials can be controlled during machining, it is often considered by manufacturers in order to increase the life of the products [7]. Various kinds of surface effects can be of great importance to the fatigue life. Surface effects include all conditions capable of reducing or enhancing the crack initiation period [8]. Bayoumi [9] studied the effect of surface finish on fatigue strength. Surface roughness of each group of specimens was measured and the quality of surface evaluated from the profile graph. Low-cycle fatigue tests subject specimens to repeated stress or strain until failure occurs at a relatively small number of cycles [10]. The upper limit in low-cycle life has generally been selected arbitrarily by individual investigators to lie in the range of 10^2 to 10^5 cycles. A study on effect of low cycle fatigue on surface finish was conducted by Kuroda and Marrow [11]. Nitriding is a thermo chemical surface treatment in which nitrogen is transferred from an ammonia atmosphere into the surface of steels at temperatures within the ferrite and carbide phase region [12, 13]. The fatigue life prediction of components have drawn more interests in many fields, in recent times. Reliable life prediction method

is an important way to improve service performances and control failure accidents. The surface roughness and heat treatment are important factors affecting the fatigue life [18-22].

2. EXPERIMENTAL PROCEDURES

SAE 1035medium carbon steel was selected as a material of study. Standard fatigue specimens were prepared according to Avery Dennison machine 7305 Fatigue Testing standards. From the material used, hour-glass shaped specimens were turned to shape with surface roughness of Ra ≈1.58 μm. These conditions were selected from the response surface to obtain surface finish that were close the average roughness required [14]. The population of specimens with this surface roughness is later referred as series F. Three additional series were created out of series F. Another one was grinded (G) to an average surface roughness of Ra 1.38 (series G). Series T were lathe turned with Ra 0.86. The last series (P) were polished with Ra value of 0.32. Surface roughness of the specimens was measured using Surface Roughness Tester (TR100).The stair case method was used in applying the moment. The applied bending moment was increased by a fixed increment and the next specimen was tested with the new bending moment.

The fatigue test of the material in air was done for the as received materials (SAE 1035 Steel). The bending moments imposed were 681.7, 1022.6, 1363.5, 1704, and 2045KN-m for the various Surface finish. The bending test was performed at a frequency of 50Hz (1400 rpm) for each specimen. This was a complete reversed cycle of stress range and is equal to minimum stress divided by maximum stress which is equal to a negative value (-1) in fatigue tests. Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature range (500 to 550°C), while it is in the ferritic condition. The samples were heated in an atmosphere of hydrocarbon mixed with Ammonia (NH₃). It was then cooled in the atmosphere. Because nitriding does not involve heating into the austenite phase and a subsequent quench to form martensite, nitriding was accomplished with a minimum of distortion and with excellent dimensional control.

2.1. Mathematical Models Development

The test model programme was divided into the following three groups:

Polished Group 1 with mean average roughness of (Ra=0.32 μm). Five specimens were tested at low cycle fatigue to obtain fatigue data at constant amplitude loading and zero mean stress.

Grinded Group 2 with mean average roughness of (Ra= 0.86 μm). Five specimens were tested in this group.

Lathe Turned Group 3 with mean average roughness of (Ra= 1.58 μm). Five specimens of average roughness 1.58 μm were. The S-N curve equation for the data was formulated as follows (using the least square method in MATLAB computer simulation):Nitrided

Polished:

$$\sigma = 23840 N_f^{-0.3010} \tag{1}$$

(Grinded:)The S-N curve equation which describes the results in the table is:

$$\sigma = 23240 N_f^{-0.4508} \tag{2}$$

(Turned:) The S-N curve equation of the results can be written as:

$$\sigma = 17310 N_f^{-0.3195} \tag{3}$$

Table 1gives the life prediction of specimens according to equations (1, 2 and 3).Knowing that the stress value used in these equations is the average value of the variable applied stresses equations (1 - 3).

Table1. *The life prediction of specimens according to equations (1, 2, 3)*

Stress (N/mm ²)	N _f (based on eq.1)	N _f (eq.2)	Ks	N _f (eq.3)	Ks
681.7	3568.16	4581.14	1.28	1408.95	0.395
1022.6	969.9	1177.56	1.21	548.3	0.57
1363.5	384.9	449.1	1.17	280.7	0.73
1704	188.1	212.8	1.13	167.1	0.89
2045	104.7	115.52	1.10	109.3	1.04

Surface roughness factor (Ks) is defined by the following [15]

$$K_s = \frac{N_f(\text{for actual speciman})}{N_f(\text{for roug h, polis hed})} \tag{4}$$

It is clear from Table 2 that the value of Ks (smooth surface) equals unity while Ks (medium surface) equals to (0.89) and Ks (rough surface) equals to (0.395).

Table2. Surface roughness factor (Ks),

Specimen No.	Ra μm	Kc(based on Equ(1))	Kc (2)	Kc(3)	Kc (4)	Kc(5)
E1	(0.32μm)	5.23	1.42	(0.56)	0.17	0.15
E2	(0.86μm)	4.48	1.15	(0.44)	0.21	0.11
E3	(1.38μm)	1.03	0.40	(0.21)	0.12	0.08
E4	(0.32μm)	2.26	(0.88)	0.45	0.27	0.18

Correction factor (Kc) is calculated from the comparison between the experimental and predicted life of each specimen, Table 3 [16].

$$K_c = \frac{N_{f\text{ experimental}}}{N_{f\text{ predicted}}} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. Effect of Surface Finish on Fatigue Strength

Figure 1 shows S-N Curve for nitrided samples. As evident in this figure, there is a notable difference in fatigue strength amongst the specimens, although high plastic deformation and the machined surface finish continued to contribute to fatigue damage accumulation. The rate of damage and the corresponding contribution of surface finish to fatigue failure of the medium carbon steel specimens with larger roughness were faster in the case of grinded specimen. Nitriding has the combined effect of producing a higher strength material on the surface as well as causing volumetric changes which produce residual compressive surface stresses. After the nitriding treatment, a compound layer and an underlying diffusion zone (case) were formed at the surface of the medium carbon steel. The compound layer, also known as the white layer, consists predominantly of Fe₄N as nitrogen has partial solubility in iron. In the region beneath the compound layer, that is the case, for pure iron, nitrogen from outside dissolves interstitially in the ferrite lattice at the nitriding temperature. The hardened diffusion case is responsible for a considerable enhancement of the fatigue endurance.

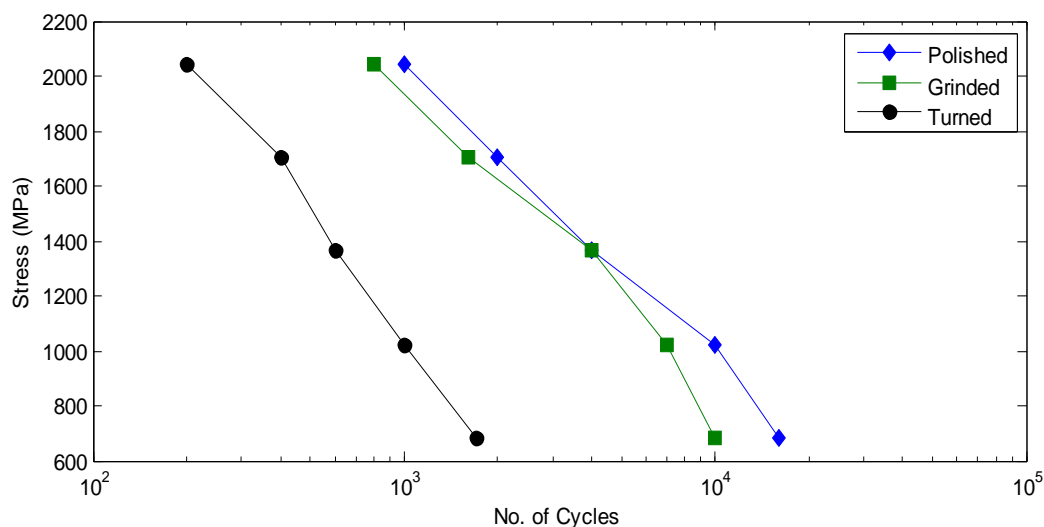


Figure1. S-N Curve for Nitrided samples

3.2. Hardness Test

Hardness values for the samples are shown in figure2 (a).Hardness test results show the variation with respect to both surface finish and the different heat treatment conditions. These are results which interpret the difference in heat-treatment types and it also helps to understand the mechanism behind the property alteration. Mechanical properties are enhanced as the materials passed through the heat

treatment processes. In this research, specimens corresponding to all carburized heat-treatment temperatures showed higher hardness as compared to the nitrided specimens of the same steel. From the figure, it is observed that the polished and nitrided specimens are softer than that of the turned and grinded heat-treated samples. The rougher samples attained higher surface nitride concentration and revealed greater hardness gain. The lathe turned (nitrided) samples, where the measured surface roughness ($Ra = 1.38$) was larger than those of the other samples provided a greater number of sites available for nitride molecules deposition. This, in turn, increased the density of adsorbed nitride atoms and enhanced nitride diffusion flux from the steel surface to the bulk of the material. As a result it has higher hardness value of 321 HBR as compared to the polished (nitrided) samples having hardness value of 170 HBR.

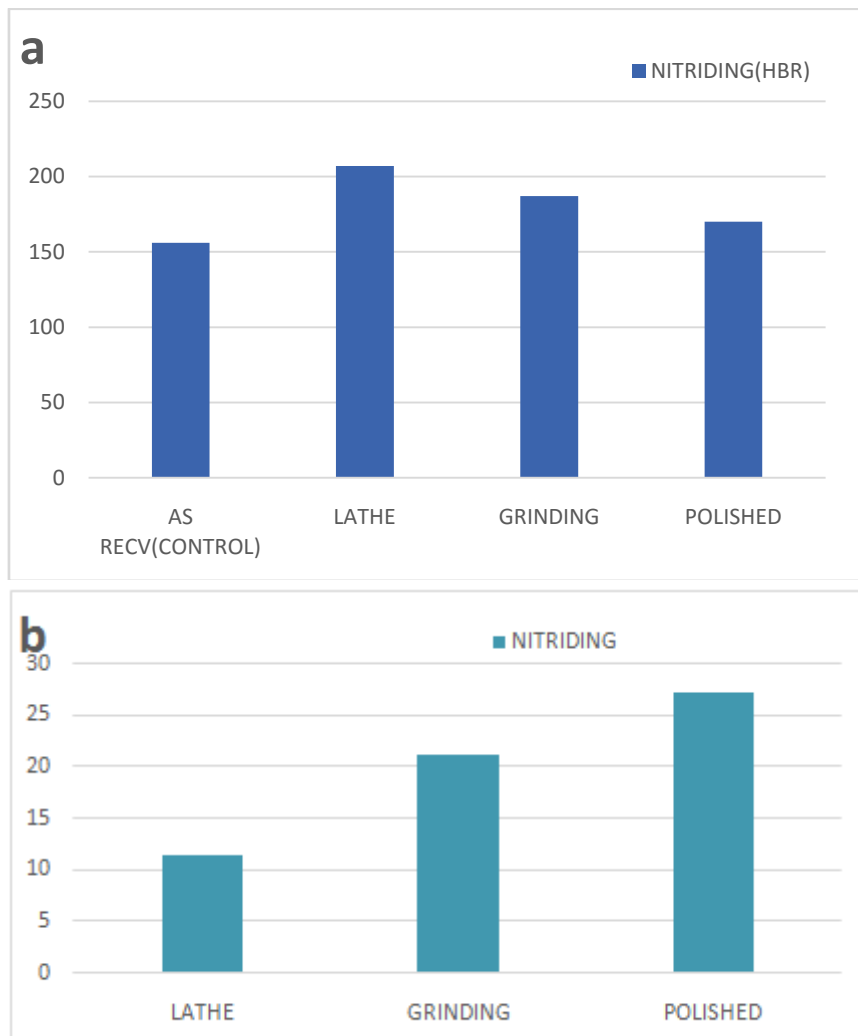


Figure 2. (a) Hardness of surface finished and heat treated specimens, (b) Impact test of surface finished and heat treated specimens

3.3. Impact Test

Figure 2 (b) shows the impact test results. Due to the refinement of the case and the core of the medium carbon steel sample with the heat treatments, it was observed that the polished and nitrided sample has the highest toughness followed by grinding leaving the lathe turned with the least energy/resistance to fracture.

3.4. Proposal of a Model for Predicting Fatigue Life

The S-N curve equation for the data was formulated (using the least square method in MATLAB computer simulation):

Generally an increase in surface roughness is accompanied by a decrease in fatigue strength and in fatigue life. [17] Also it is clear that, from table 3, for high surface roughness (rough surface) Kc is

about 0.21 based on equation 3 while this value becomes 0.44 based on equation 2 and 0.56 based on equation 1.

Table 3. The values K_c of cumulative fatigue specimen tests.

	Specimen No.	(A) N_f predicted Cycles	(B) N_f predicted Cycles	(C) N_f predicted Cycles	(D) N_f predicted Cycles	(E) N_f predicted Cycles
As Received	E1(0.32 μ m)	3568.16	969.9	(384.9)	188.1	104.7
	E2(0.86 μ m)	4581.14	1177.56	(449.1)	212.8	115.52
	E3(1.38 μ m)	1408.95	548.3	(280.7)	167.1	109.3
	E7(0.32 μ m)	134466.6	(34956.1)	13440.3	6408.65	3495.94
Nitrided	E8(0.86 μ m)	(2510.9)	1021.3	539.5	329	219.53
	E9(1.38 μ m)	24921.2	7004.16	2846.3	1416.6	(800.38)

This difference in K_s values is due to the difference in surface roughness value (R_a). In order to avoid the large error in life prediction and to make K_c about unity, it is necessary to take into account the roughness (R_a) especially when the difference in (R_a) value is big. A new model is developed which takes into account the difference in (R_a) values. This model is written as:

As Received, $\sigma_f = 10837(R_a)^{-0.17} N_f^{-0.3705}$ (6)

Nitrided, $\sigma_f = 21463(R_a)^{-0.24} N_f^{-0.38515}$ (7)

The above equations are developed based on experimental data of the groups 1, 2 and 3. Using the least square method in MATLAB software. Figures 3 shows the predicted number of cycles to failure using equation (6 and 7).

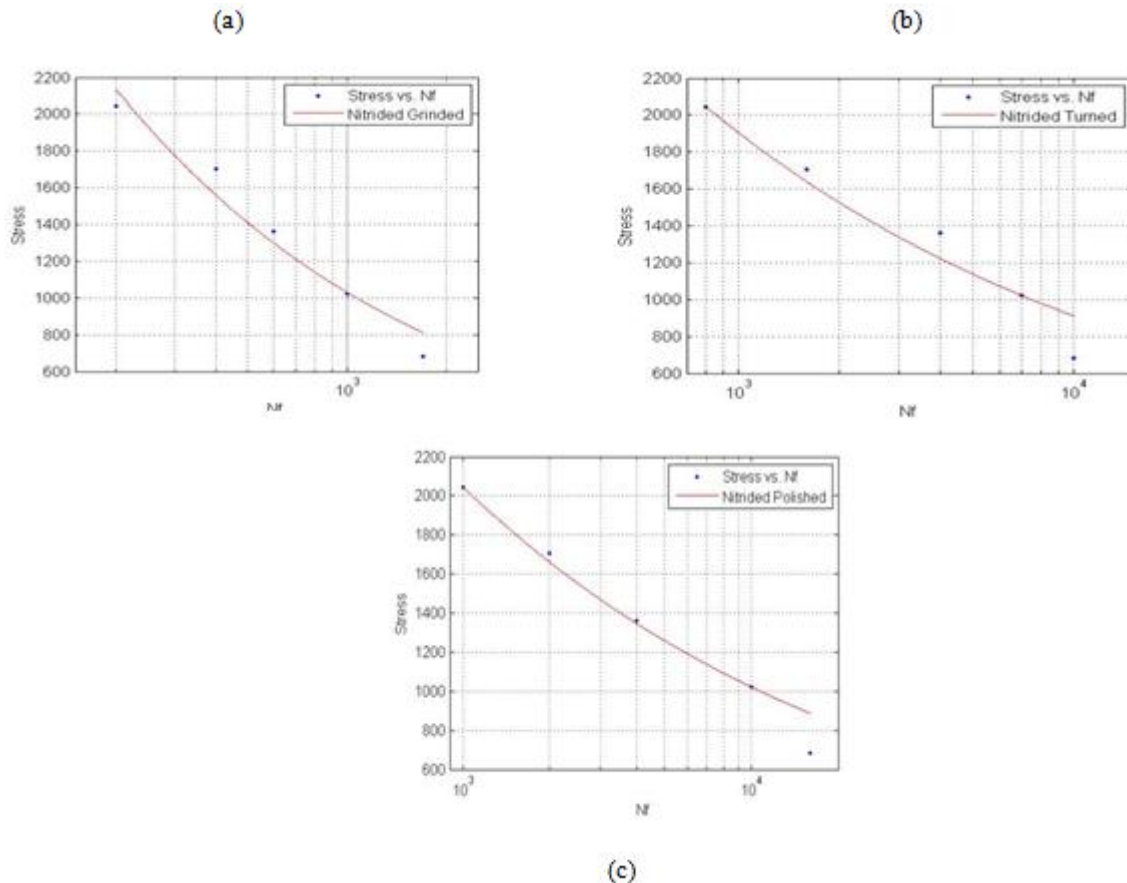


Figure 3. (a) model generated for nitrided Grinded, $\sigma = 23240 N_f^{-0.4508}$, (b) model generated for nitride Turned, $\sigma = 17310 N_f^{-0.3195}$, (c) model generated nitride Polished, $\sigma = 23840 N_f^{-0.3010}$

A comparison between the predicted number of cycles to failure and the experimental result is shown

in figure 4. It is clear that when using equations 6 and 7, the life predictions are in good agreement with the experimental life. Therefore Equations 6 and 7 validates the experimental results.

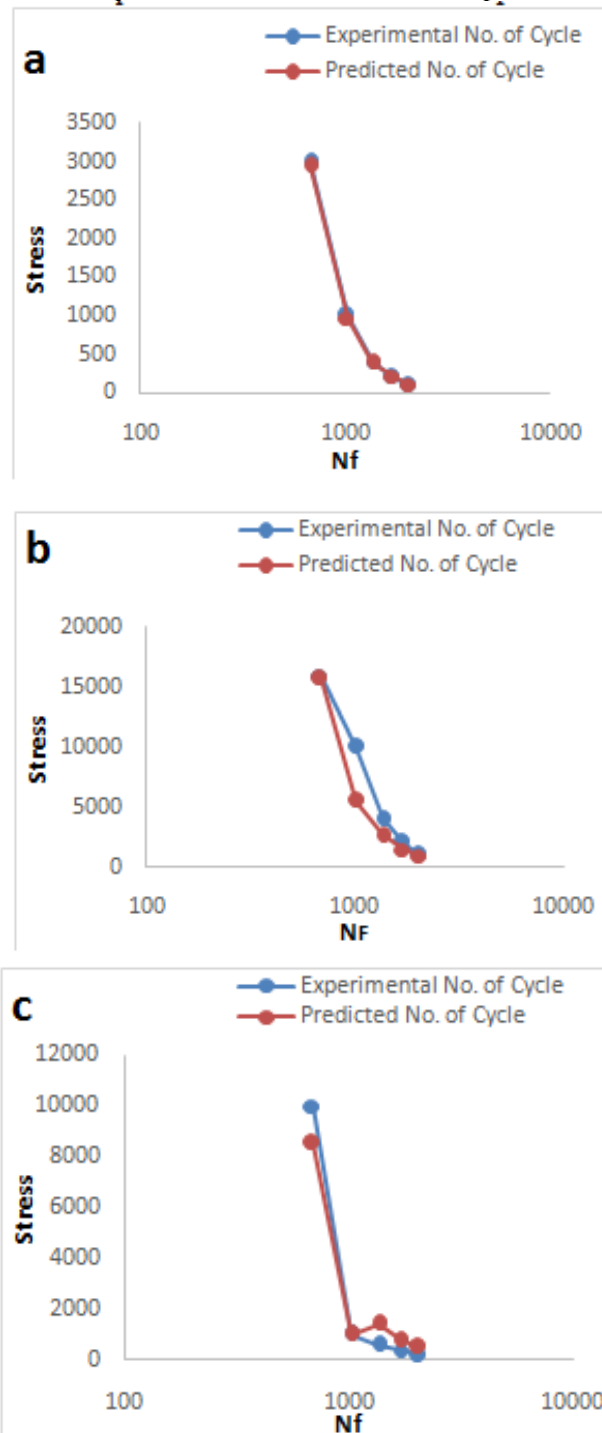


Figure 4. Comparison of Experimental and Predicted number of cycles (N_f) for (a) Polished As received, (b) Polished Nitrided, (c) Grinded Nitrided

4. CONCLUSION

Tests to determine the mechanical properties of SAE 1035 steel in the as-received condition revealed that the SAE 1035 had a hardness of 156 HB as compared with a brinell hardness of 207 HB for nitrided specimens lathe turned respectively. It is concluded that the differences in hardness levels are largely responsible for the differences shown in the S-N curves. The impact properties indicated that the nitrided specimens had the highest toughness/ resistance to fracture compared to the as-received specimens. The S-N curves for completely reversed bending were first established for the material tested in the as-received condition. S-N curves were drawn to examine the effect of machined surface quality (surface finish) on the fatigue life of the medium carbon steel specimens with varying surface

roughness. The bending strength was plotted against the Number of cycles to failure. It was observed that the fatigue life increased as the bending load on the specimen decreased. It was also found that the surface with lower surface roughness (polished specimen; $R_a = 0.32 \mu\text{m}$) has better fatigue life. The lathe turned surface with higher roughness (turned; $R_a = 1.58 \mu\text{m}$) however showed relatively lower fatigue life. Thus, it is concluded that polished surface increases the fatigue life of machined components when compared to grinded and lathe turned specimens. This is because rough surfaces form stress concentration centers, thus leading to decreasing endurance limit. Results on nitrided specimens illustrate the dependence of the fatigue behavior on case hardening process control and microstructure. It was shown that significant gains in the fatigue performance of case-hardened medium carbon steels was realized through nitriding heat treatment. The best results were obtained for the polished specimen nitrided with lower surface roughness ($R_a = 0.32 \mu\text{m}$). These specimens have also shown the highest endurance limit. This is perhaps, due to the fact that after heat treatment these specimens possessed very high strength with significant ductility. The results show that, polishing and nitriding are the best surface finish and heat treatment options respectively. It is therefore concluded that the specimen having higher compressive residual stresses built up bear higher endurance limits. Roughness of the surface is important factor and must be taken into consideration for prediction of fatigue life. The application of the developed models to the fatigue specimens validated the experimental results. A new life prediction model is derived from this study which includes the effect of difference roughness and nitriding treatment values. This model is formulated as $\sigma_f = 21463(R_a)^{-0.24} N_f^{-0.38515}$

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