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ANALYSIS OF THE FATIGUE BEHAVIOR OF NST 37-2 STEEL BASED ON PROBABILISTIC STRESS-LIFE (P-S-N) RELATIONSHIPS

B.O. Malomo
Departments of Mechanical Engineering,
Obafemi Awolowo University, Ile-Ife, Nigeria.
babfem@yahoo.com

S.A. Ibitoye
Materials Science and Engineering,
Obafemi Awolowo University, Ile-Ife, Nigeria.

L.O. Adekoya
Departments of Mechanical Engineering, Obafemi Awolowo University,
Ile-Ife, Nigeria.

ABSTRACT

A new data analysis method proposed by Shimizu et al. (2010) which defines the physical meaning of the statistical parameters in the Weibull distribution function based on the theoretical consistency between material life distributions and probabilistic stress life (P-S-N) curves was applied in this study to analyze the fatigue behavior of locally-rolled NST 37-2 steel. Tensile tests were carried out to establish the baseline material properties of the steel. Fatigue tests were conducted at 60-80% S_u of the test material and then fractured surfaces were examined. Weibull plots were obtained through linearized transformations and compared with representative relations from the proposed new method of analysis. The results obtained showed a non-conservative trend in the classification of the fatigue performance of the test material in as-rolled, annealed, normalized and hardened/tempered conditions. Thus, test material may be useful in low cycle quasi-static applications.

Keywords: *Fatigue behavior, Probability-stress-life, Weibull plot, Steel.*

1. INTRODUCTION

Fatigue life prediction of engineering materials, structures and systems is an indispensable task in a reliable engineering design process whenever cyclic loading conditions are involved (Savaidids et al., 2001). Fatigue failures are notably fragile failures usually accompanied by mechanical actions which may not seem critical by themselves but in the end are decisive for the life of the structure or material. According to Schijve (2003), this engineering problem had been recognized since the early decades of the 20th century and prevention of associated failures has continued to be the central focus of extensive research. Prediction models have been developed based on the understanding that structures are rarely stressed repeatedly at a single load level and the failure of the structure is therefore, the result of fatigue damage accumulation caused by the multiplicity of loading cycles having different amplitudes and loading frequencies (Memon et al., 2002). Earlier attempts to evaluate fatigue behaviour had been based on the application of the Wohler's S-N curves, a conservative procedure that has now being efficiently replaced by fracture mechanics and continuum-based approaches. However, regardless of the fracture mechanics method employed, the increasing demand from design engineers for data concerning statistical fatigue life distribution of various materials in reliability assessment has prompted the recent re-evaluation of the Wohler's approach and its subsequent modifications in various applications (Achutha et al., 2008; Makkonen, 2009). Susmel (2009) reported a novel engineering method to estimate the fatigue lifetime of aluminum welded joints subjected to constant amplitude fatigue loading based on the modified Wohler curve method (MMWCM). Shimizu et al. (2010) have also developed a probabilistic-stress-life criterion for application to structural materials. A practical evaluation of this concept had been demonstrated by Zhao et al. (2010) in estimating the probabilistic fatigue S-N curves on the basis of super-long life requirements of structural steel material for railway applications. Furthermore, in order to accurately predict the S-N curve of high strength steels in very high cycle fatigue a new method based on the Basquin's equation has also been proposed (Liu et al., 2010). Fatigue lives exhibit considerable scatter even under constant amplitude loading in controlled laboratory conditions. This phenomenon makes statistical methods indispensable and fatigue lives have to be predicted at given probability levels of failure (Recho and Lassen, 2009).

The present paper therefore seeks to investigate the fatigue behaviour of NST 37-2 steel by providing a physical understanding to this property in line with the recommendations of Shimizu et al. (2010).

2. THE NEW WEIBULL-BASED P-S-N STATISTICAL DISTRIBUTION FUNCTION

In response to the deficiencies highlighted above in directly applying test *S-N* (stress-life) data for the determination of probabilistic *S-N* curves, a mathematical model has been formulated by Shimizu et al. (2010) for a statistical representation of the fatigue process:

$$N_n - \gamma = B\left(S - S_f\right)^{-A}, \gamma \geq 0, S_f \geq 0 \qquad (1)$$

$$ln\left(N_n - \gamma\right) = -A ln\left(S - S_f\right) + lnB \qquad (2)$$

where, N_n = n% fatigue life,
A = the stress-life exponent,
B = the fatigue strength coefficient and;
γ = the minimum life.

The three-parameter Weibull distribution which considers the probability that the material will not fail with n% failures (i.e. with a reliability of R = $1 - {}^{n}/_{100}$) can be expressed as;

$$\ln {}^{1}/_{R} = \left(\frac{N_n-\gamma}{\eta}\right)^m \tag{3}$$

where m = Weibull slope and;
η = scale parameter.

For the case where n = 10% and R = 0.9 the scale parameter can also be expressed as;

$$\eta = (N_{10}-\gamma)\left(\ln\frac{1}{0.9}\right)^{-1/m} \tag{4}$$

By introducing a new parameter, i.e. basic dynamic stress rating $C_s = B^{1/a}$, then $N_n - \gamma$ can be written in the form,

$$N_{10} - \gamma = \left(\frac{S-S_f}{C_s}\right)^{-A} \tag{5}$$

The Weibull regression equation can thus be described by;

$$ln(N_{10}-\gamma) = -Aln(S-S_f) + lnB, B = {C_s}^A \tag{6}$$

By combining Equations 3-6, a life $N_n - \gamma$ for an arbitrary reliability R included in a reliability factor a1 can be obtained:

$$N_n - \gamma = a_1\left(\frac{S-S_f}{C_s}\right)^{-A}, a_1 = \left(\frac{\ln R}{\ln 0.9}\right)^{1/m} \tag{7}$$

The minimum life is thus;

$$\gamma = \left(\frac{S-S_f{}'}{C_s{}'}\right)^{-A'} \tag{8}$$

A P-S-N curve of the form,

$$N = a,\left(\frac{S-S_f}{C_s}\right)^{-A} + \left(\frac{S-S_f{}'}{C_s{}'}\right)^{-A'} \tag{9}$$

is obtained, where $S_f{}'$, $C_s{}'$ and A' are replacements for, $S_f, C_s and$ A respectively.

The probability density function $f(N_n)$ for the Weibull distribution can thus be obtained from the relation;

$$f(N_n) = \frac{m(N_n-\gamma)^{m-1}}{\eta^m} exp\left(-\left(\frac{N_n-\gamma}{\eta}\right)^m\right) \tag{10}$$

3. MATERIALS AND METHODS

3.1. Test Material and Specimen Preparation

The material investigated in this study was NST 37-2 steel with chemical composition as shown in Table 1. The sample material was machined to the appropriate geometries required for mechanical testing in accordance with ASTM E8-04 and ASTM E466-82 specifications as shown in Figures 1 and 2 respectively. The gauge portion of each specimen was polished to remove all forms of surface irregularities that may have been introduced during machining.

A total of 240 test specimens were classified into four equal groups, three sets out of which were subjected to annealing, normalizing and hardening/tempering treatments in accordance with the procedures given by Rajan et al. (1988). The fourth group of test specimens was not treated.

Table 1: Chemical Components of NST 37-23 Steel

Element	C	Si	Mn	P	S	Cu	Cr	N	Sn	Fe
Weight (%)	0.20	0.37	0.65	0.04	0.05	0.70	0.70	0.01	0.05	Balance

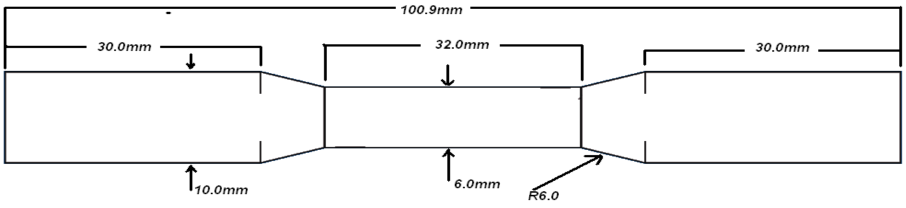

Figure1: Tensile test specimen

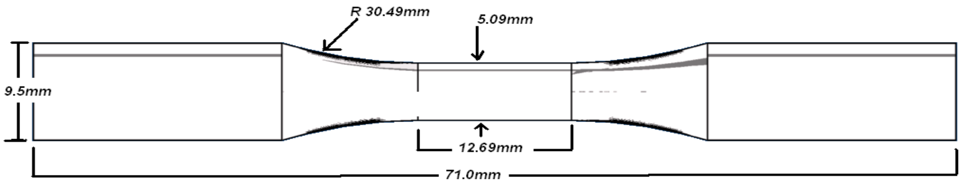

Figure 2: Fatigue test specimen

3.2. Test Conditions

Stress-strain tests were performed using an Instron tensile testing machine to determine baseline material properties. The fatigue tests were carried out at ambient temperatures under constant amplitude loading of a four-point rotating bending fatigue-testing machine operated at a load ratio of R = -1. The behaviour of the test material was investigated under loading conditions of torsion and the operating stress levels were chosen at 60, 70 and 80 % of the ultimate tensile strength of the test material, in accordance with the theory of finite life estimation of fatigue behavior (Lipson and Sheth, 1973; Hadlar and Mahadevan, 2000).

Tests were conducted on groups of as-rolled, annealed, normalized and hardened/tempered specimens from NST 37-2 steel; and their representative numbers of stress cycles to failure were recorded (Achutha et al., 2008; Lipson and Sheth, 1973). The tests were conducted at random to minimize the effect of uncontrollable variables. Morphological characteristics of fractured specimens were analyzed by fractographic investigations using a scanning electron microscope (SEM).

4. RESULTS AND DISCUSSION

4.1. Experimental Data

Table 2 presents the details of the data obtained from tensile testing which provides the input for fatigue testing at stress levels chosen at 60, 70 and 80% of the ultimate tensile strength of NST 37-2 steel.

4.2. Analysis Based on Weibull Statistics

The experiments were conducted based on the assumption that the scatter of statistical curves are usually non-symmetrical, which allows the application of the Weibull probabilistic density function in the analysis of experimental data. The analysis was carried out in a MATLAB environment after an appropriate code has been written for the three-parameter evaluation.

Linearization transformations of experimental data based on median ranks of percentage of failure and the corresponding fatigue lives were carried out to generate the Weibull plots of Figures. 3-6. The probability of stress-life relationships as shown in Figures 7-10 were determined based on the predicted values of regression models (Appendix A), through the linearized transforms of percent failure and fatigue lives at each stress level for the groups of as-rolled, annealed, hardened/tempered and normalized test specimens, respectively. This analysis is necessary in order to meet the requirements for the fatigue reliability assessment due to the well-known fact that it is impractical to estimate the cyclic stress at which a component fails at a given life in advance. Thus life prediction requires the use of *S-N* curve with a given survivability (Zheng et al., 1995).

Table 2: Baseline Material Properties of NST 37-2 Steel

Specimen	Young's modulus (Mpa)	Poisson ratio	Yield strength (Mpa)	Tensile ultimate strength (Mpa)	Bulk Modulus (Mpa)	Shear Modulus (Mpa)
Annealed	2.1 E 11	0.3	4.17 E 0.8	6.55 E 08	1.75 E 11	8.0769 E 10
As-rolled	1.8 E 10	0.28	4.17 E 0.8	6.55 E 08	1.3768 E 11	7.4803 E 10
Hardened/Tempered	1.9 E 11	0.29	4.17 E 0.8	6.55 E 08	1.5873 E 11	7.7519 E 10
Normalized	2.0 E 11	0.28	4.17 E 0.8	6.55 E 08	1.4394 E 11	7.4219 E 10

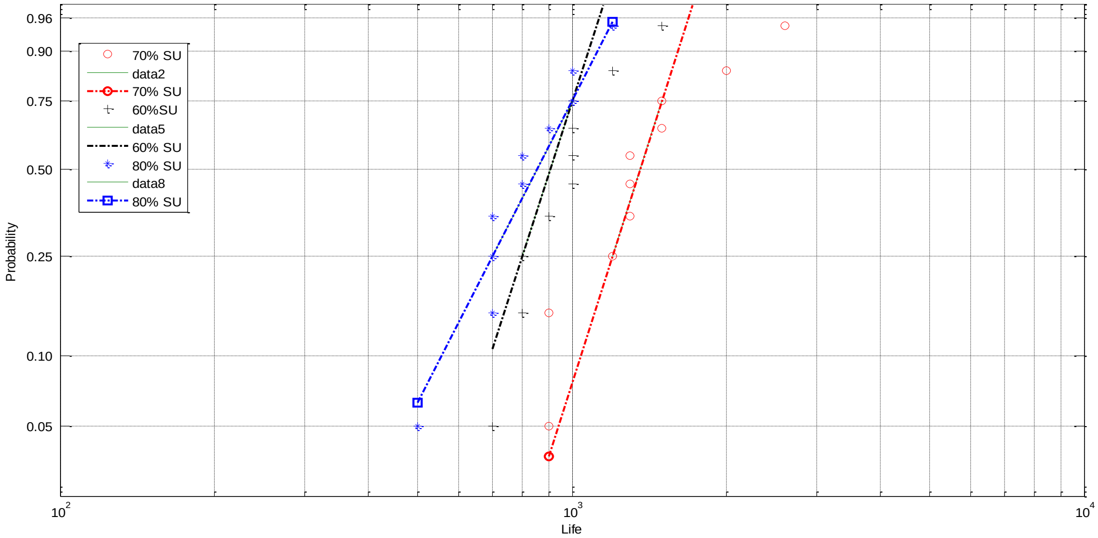

Figure 3: Probability-life plot for as-rolled specimens

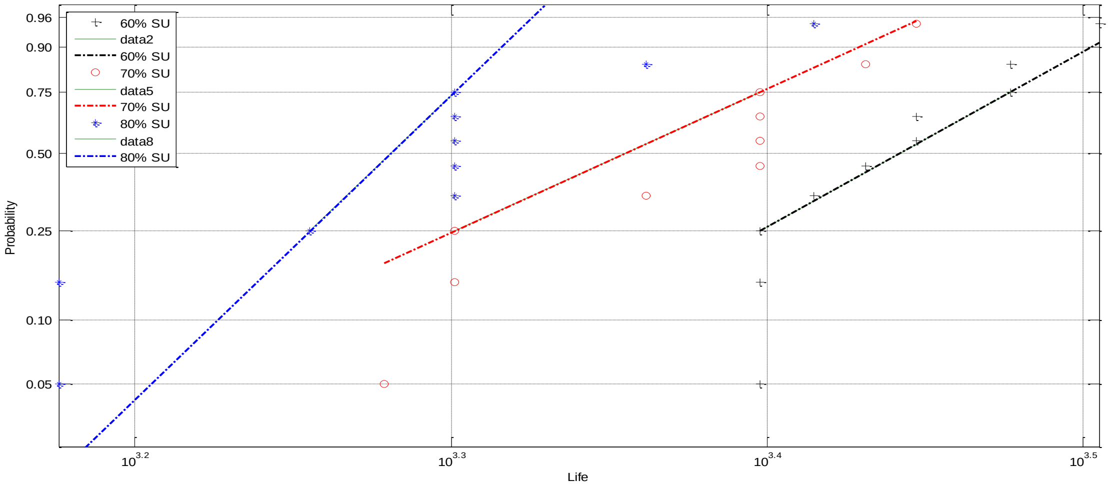

Figure 4: Probability-life plot for annealed specimens

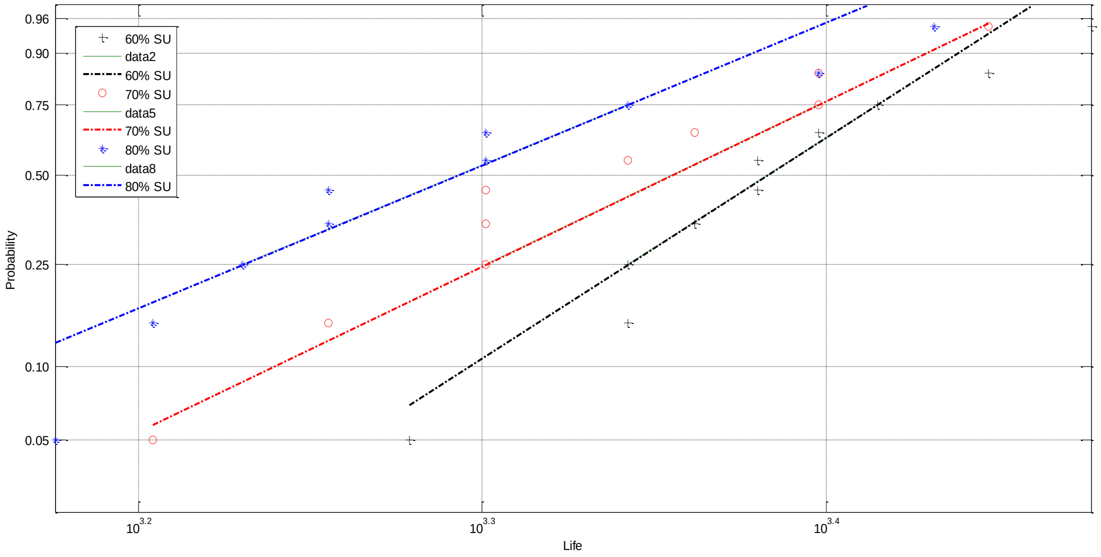

Figure 5: Probability-life plot for normalized specimens

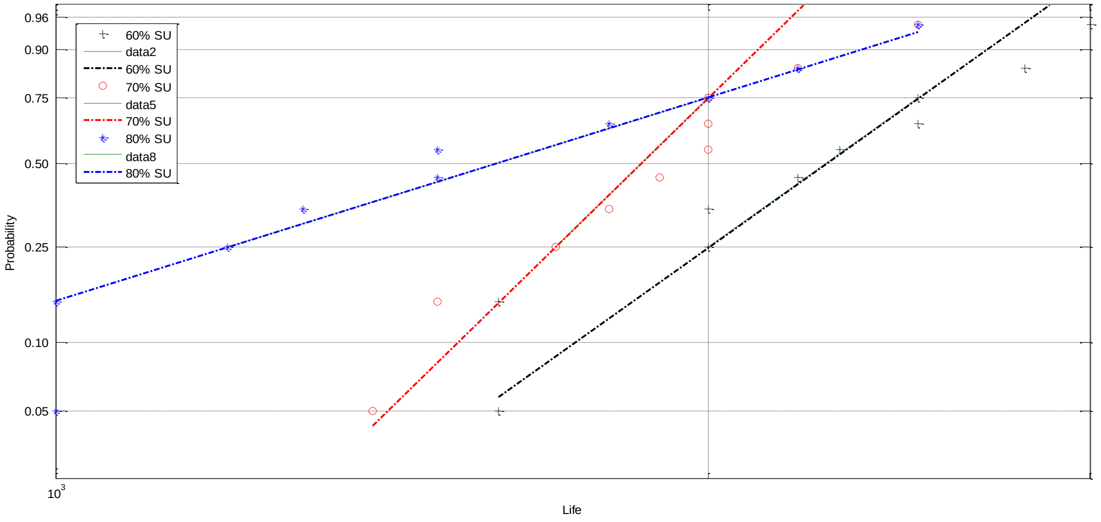

Figure 6: Probability-life plot for hardened/tempered specimens

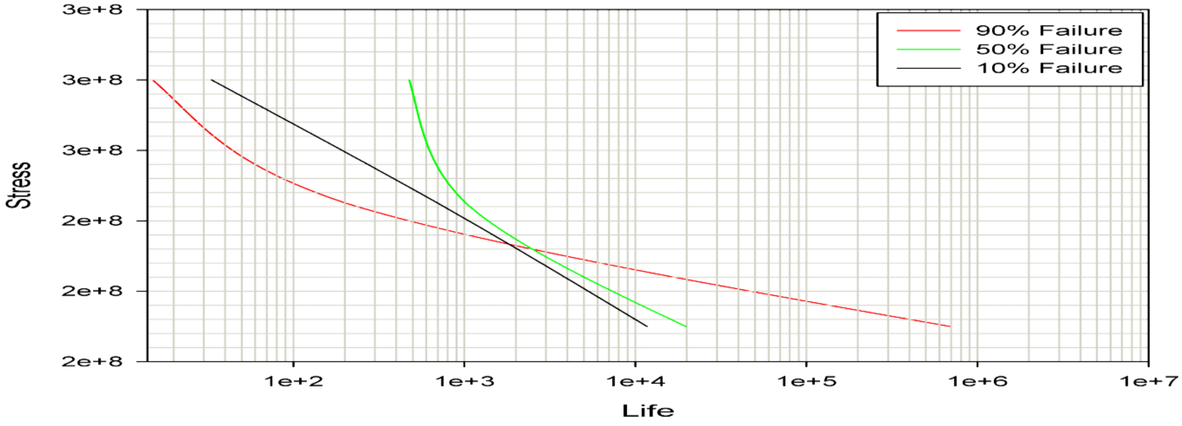

Figure 7: Probability-stress-life plot for as-rolled specimens

Figure 8: Probability-stress-life plot for annealed specimens

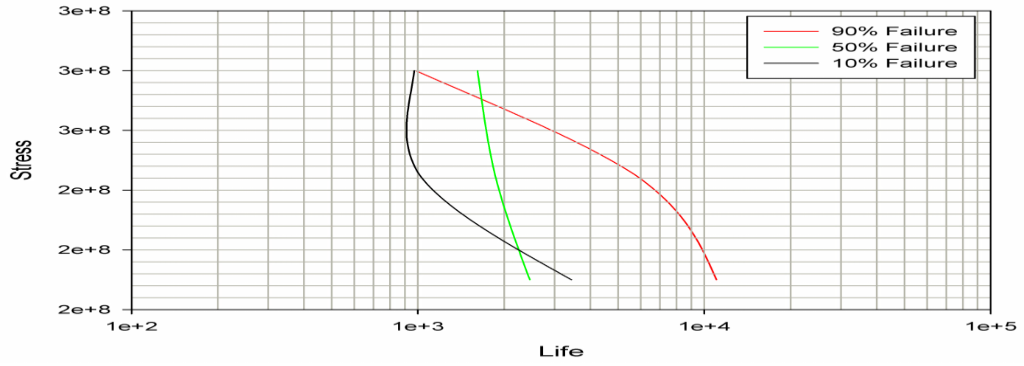

Figure 9: Probability-life plot for normalized specimens

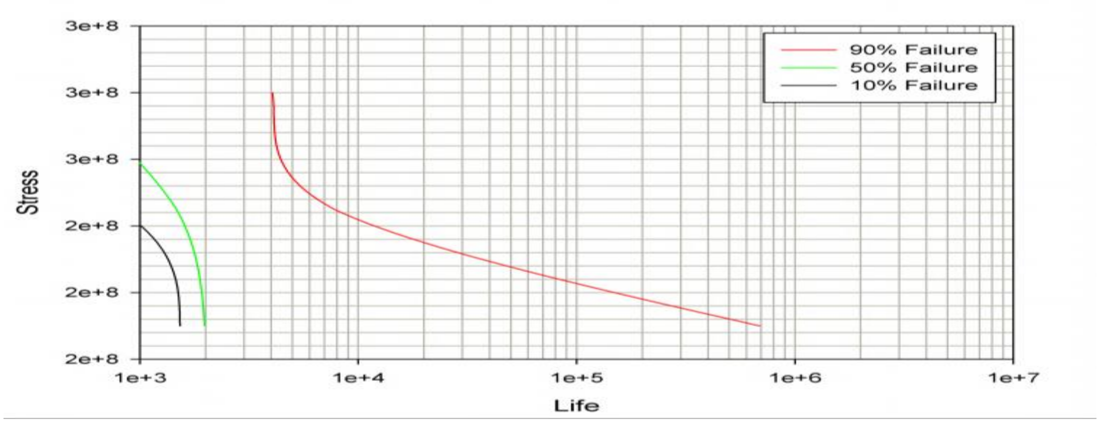

Figure10: Probability-stress-life plot for hardened/tempered specimens

Table 3: The Weibull Slope Values for the Groups of Test Specimens at the Three Stress Levels of Testing

	As rolled	Annealed	Hardened/Tempered	Normalized
Stress(pa)	slope (*m*)	slope (*m*)	slope (*m*)	slope (*m*)
1e8	0.7514	1.466	1.379	1.458
2e8	0.7122	1.347	1.412	1.431
3e8	0.6998	1.441	1.407	1.336

The Weibull parameter m, (slope) was used as a statistical indicator of fatigue performance for the groups of test specimens considered as presented in Table 3. The annealed test specimens group was observed to have the best fatigue resistance since the *m* value which ranges between (1.347 and 1.466) is the highest as compared with (1.336 and 1.458), (1.379 and 1.407) and (0.6998 and 0.7514) for normalized, hardened/tempered and as-rolled groups of test specimens respectively. Although these values do not vary significantly, except for the as-rolled group, the annealed specimens are still considered to have presented the least dispersion and thus a more homogenous distribution of fatigue strength.

4.3. Analysis Based on the New Weibull P-S-N curves

The *P-S-N* regression curves which indicate the probability of failure (Figures 11-14) were obtained by applying Equations 6-9 to the test data. For each test group, the final *P-S-N* formulae corresponding to each stress level with non-linearity involving the minimum life γ are shown in Appendix B. The fatigue resistance of the test specimens was considered based on the stress-life exponent and the dynamic stress rating values. The stress-life exponent *A*, which depends on the intrinsic property of the material and in this particular case, the heat treatment method applied, increases for the materials with higher fatigue resistance (Shimizu et al. 2010). The fatigue limit S_f has been assumed *a priori* in accordance with the recommendations of Lipson and Sheth (1973), under finite life estimation as 50% Su. Thus, since the stress-life exponent actually varies with the regression for each test group of specimens, the assumption may be valid and on this basis, the annealed test specimens group is once again the best in terms of resistance to fatigue. For the normalized and hardened/tempered specimen groups, the values are somewhat close. The dynamic stress rating factor C_s which indicates the load at one stress cycle for 10% failure probability according to Shimizu et al. (2010) was also considered as a criterion for making comparisons between the groups of test specimens. It is evident as detailed on Table 4 that the trends in fatigue performance still suffices, although with asymptotic conditions between the annealed and the normalized groups of test specimens. This characterization is based on the fact that the value of the slope (m) decreases with increasing stress-life exponent value (A) for the group of test specimens with the better fatigue resistance.

Table 4: Weibull-based average P-s-n functions for the groups of test specimens.

Specimen	*m*	*A*	*Cs*
As-rolled	1.106	0.2211	0.163442
Annealed	0.4305	2.323	3.4259
Hardened/tempered	0.4436	2.254	3.4610
Normalized	0.4371	2.371	3.4816

4.4. Fractographic Analysis

Figures 15 to 22 show the fractographs of the test specimens in as-rolled, normalized, hardened/tempered and annealed conditions. It is a well-known fact that fatigue fracture surfaces contain three distinct regions, namely the crack initiation area, the crack propagation area and the area of final fracture. Cracks usually initiate in the high-stress regions of a specimen, such as sharp corner features, scratch marks microstructural defects or inclusions, etc. The fatigue fracture section usually has a dimple appearance at its leading edge, but becomes progressively cleavage-type as the crack initiates, propagates and finally causes specimen fracture (Dieter, 1988).

The surface in all the cases revealed that the failure of the test specimens was governed by the coalescence of microvoids. The convergence of fracture markings into the crack initiation and subsequent propagations is also visible on the fracture surfaces. For the as-rolled specimens (Figures 15 and 16), the nucleation of crack occurred at a depth within the range of 5μm below the external surface. This may be as a result of surface inhomogeneity as the voids cluster together. A region of high stress concentration is developed within the specimen causing early crack initiation and relatively

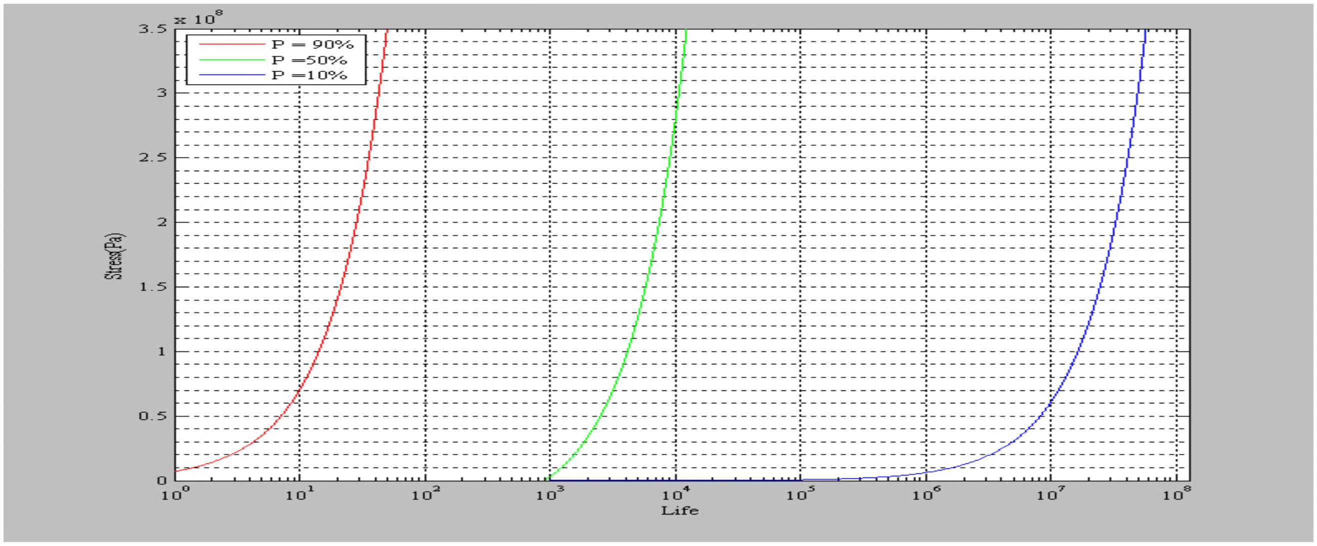

Figure 11: Probability-stress-life curves for as-rolled specimens

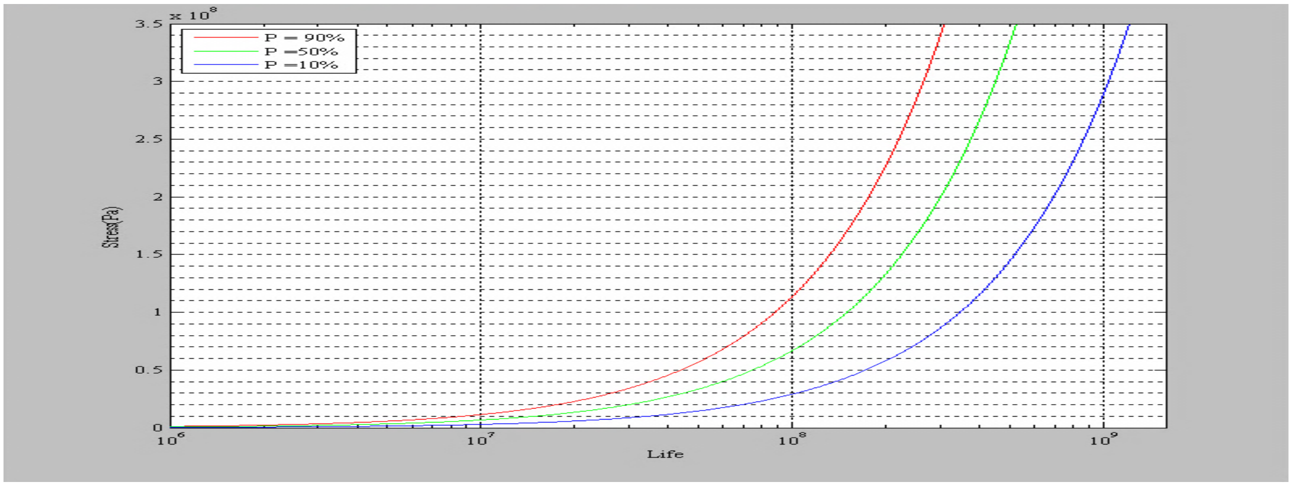

Figure 12: Probability-stress-life curves for annealed specimens

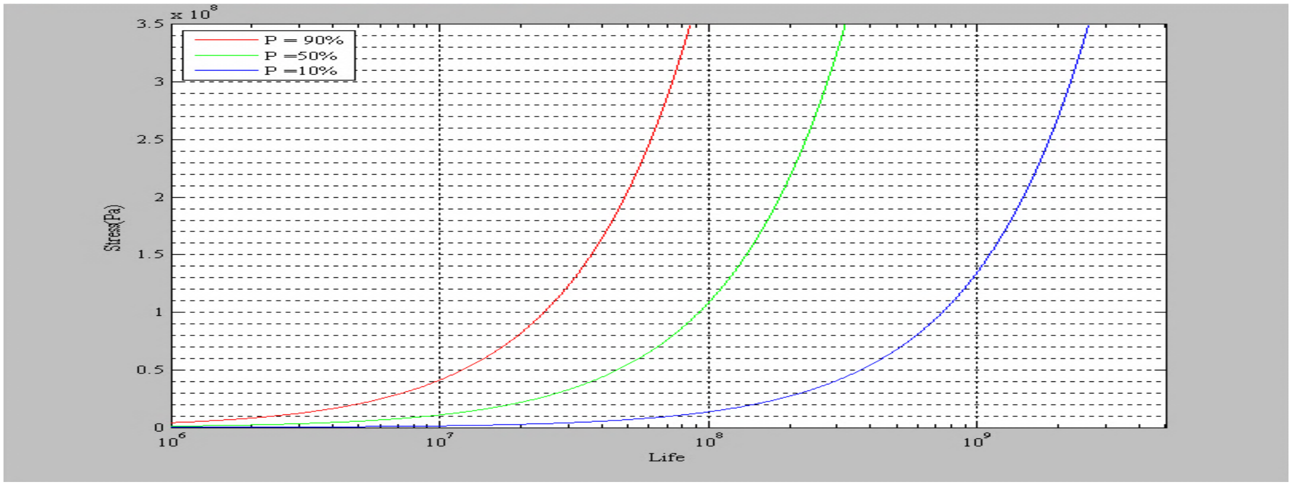

Figure 13: Probability-stress-life curves for normalized specimens

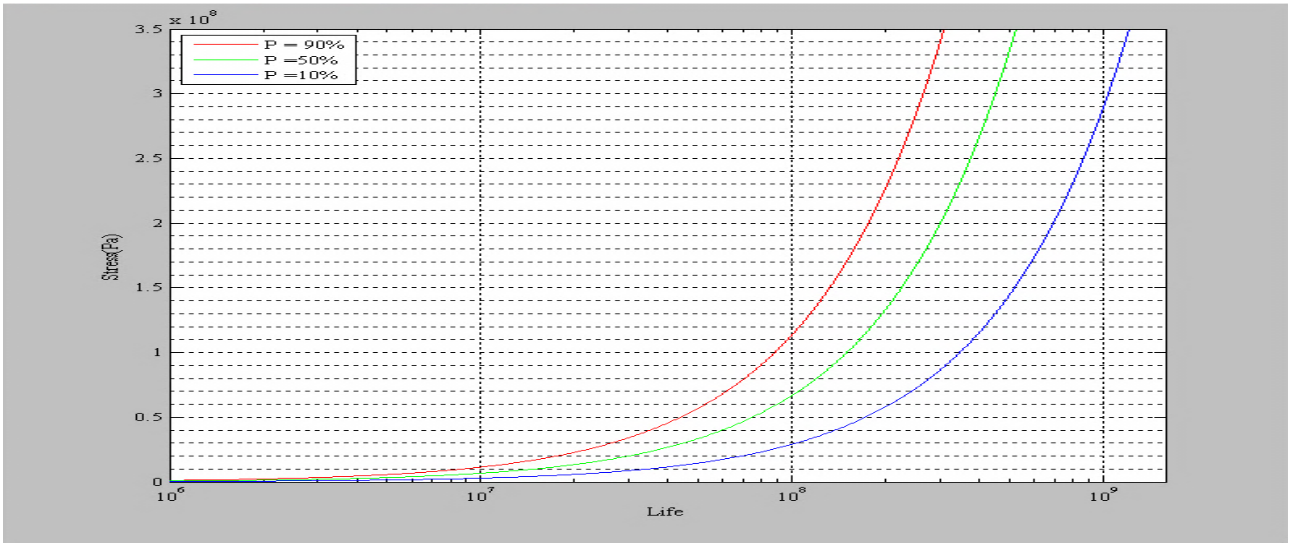

Figure 14: Probability-stress-life curves for hardened /tempered specimens

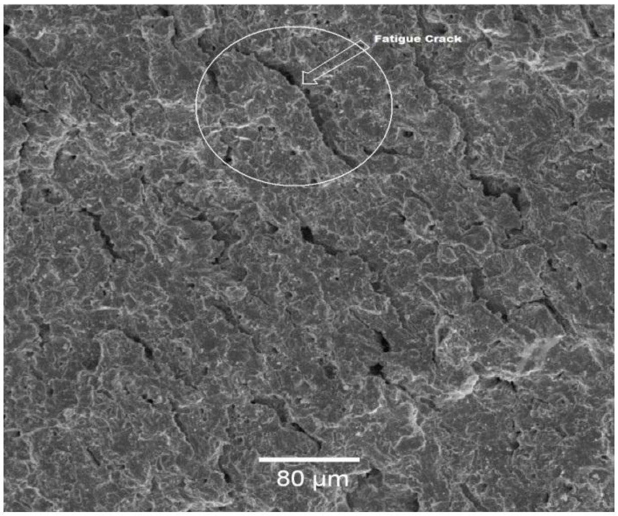

Figure 15: As-rolled specimen (a)

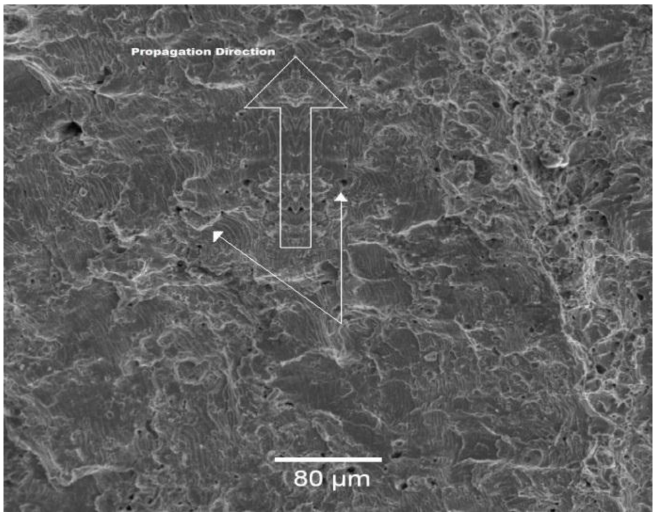

Figure 17: Annealed specimen (a)

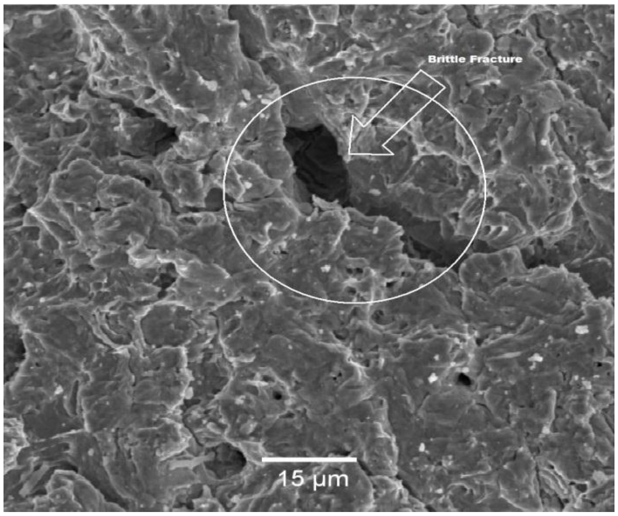

Figure 16: As-rolled specimen (b)

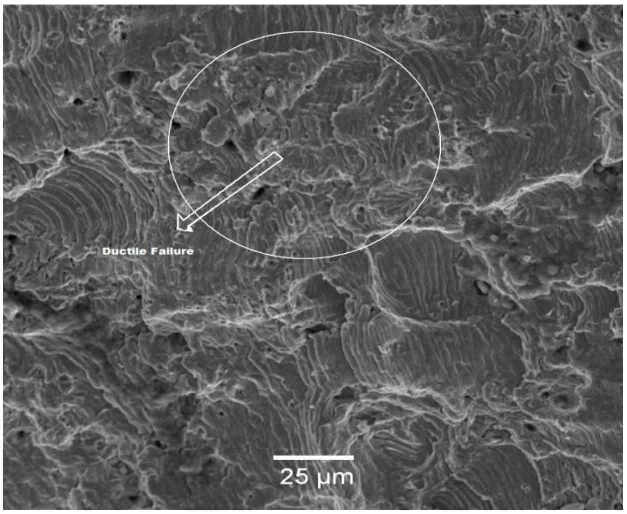

Figure 18: Annealed specimen (b)

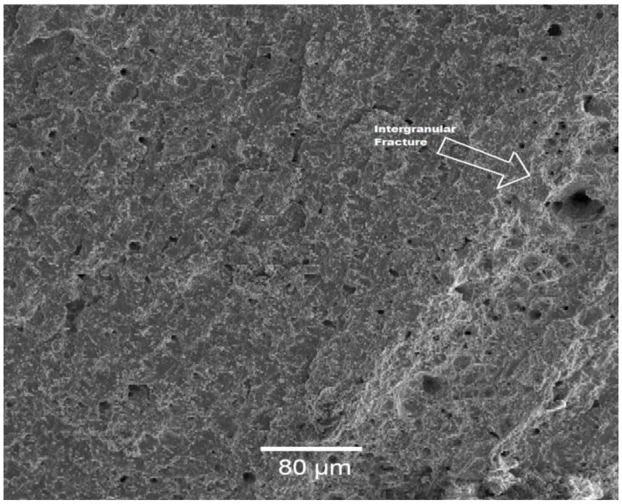

Figure19: Hardened/tempered specimen (a)

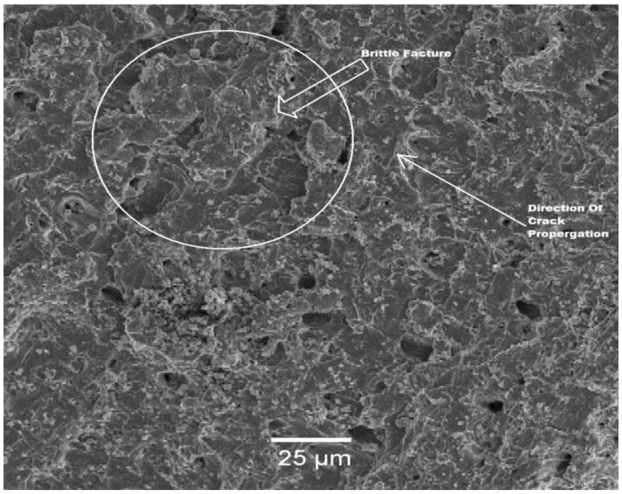

Figure 20: Hardened/tempered specimen (b)

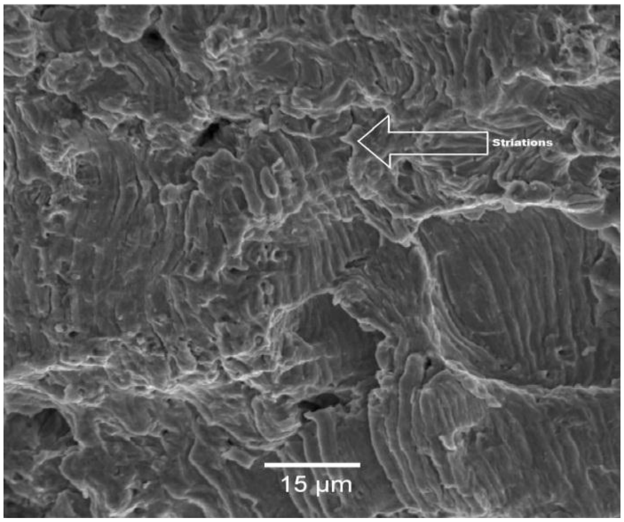

Figure 21: Normalized specimen (a)

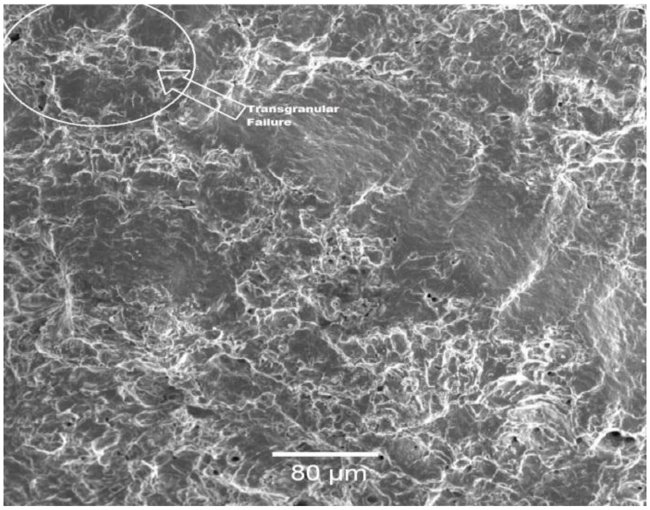

Figure 22: Normalized specimen (b)

poor fatigue resistance. From the examinations on normalized and annealed test specimens, a ductile transgranular-based fracture is dominant, which is evident by the river patterns on the fracture surfaces. The major characteristic of this type of fracture is slow crack growth rate which reduces stress concentration effects at the crack tips (Schuh et al., 2007). On the other hand, for the hardened/tempered specimens, it was observed that a mixture of intergranular and transgranular features due to the distorted fracture surfaces was evident. This type of fracture is brittle in nature and characterized by fast crack propagation where the elastic strain energy is concentrated in the small nonlinearly-deforming region ahead of the crack tip, leading to instantaneous instability. However, since the toughness of any material is determined by the intrinsic energy management mechanisms available to mitigate stress concentrations at crack tips (Schuh et al., 2007), it is evident that the normalized and the annealed specimens possess higher fracture toughness than as-rolled and hardened/tempered specimens owing to the presence of larger plastic zones. This confirms that large plastic strains are involved in the nonlinear process of energy dissipation. Thus for the annealed specimens, it can be deduced that the formation of the temper 'troostite' composed of ferrite and granular cementite derived from the instability of the martensite and residual austenite may be responsible for their higher toughness and their subsequent higher fatigue resistance.

5. CONCLUSIONS

1. The fatigue behavior of NST 37-2 steel has been analyzed with respect to the new *P-S-N* curves developed by Shimizu et al. (2010) and the method has been presented as a function comprising three parameters of stress life exponent, basic stress rating and an assumed fatigue limit. This provides an understanding to the practical interpretation of the basic Weibull distribution.
2. The *P-S-N* parameters obtained suggest that the annealed test specimen group is the best in terms of fatigue resistance. The as-rolled group on the other hand had the least fatigue behavior and the widest scatter in fatigue data distribution.
3. The fractographic characteristics of the test specimens have also been used to indicate the order of fatigue performance, which is in close agreement with the statistical estimates.

APPENDIX A

A.1: Regression models from statistical analysis of test specimens

$y = -0.0737x_1 + 0.1101x_2 + 0.3323x_3 - 3.377$ (As-rolled)

$y = -0.7743x_1 - 0.767x_2 - 0.5163x_3 + 15.07$ (Annealed)

$y = 0.7513x_1 - 0.322x_2 - 0.0737x_3 + 7.814$ (Hardened/Tempered)

$y = -0.3014x_1 + 0.5843x_2 - 0.422x_3 - 0.1306$ (Normalized)

APPENDIX B

A.2: P-S-N life formula for test specimens based on the new Weibull analysis

$$N_n = \left(\frac{S-0.5S_u}{1.163}\right)^{-0.2211} \left(\frac{\ln R}{0.9}\right)^{1/1.106} + \gamma \quad \text{(As-rolled)}$$

$$N_n = \left(\frac{S-0.5S_u}{3.459}\right)^{-2.323} \left(\frac{\ln R}{0.9}\right)^{1/0.4305} + \gamma \quad \text{(Annealed)}$$

$$N_n = \left(\frac{S-0.5S_u}{3.4610}\right)^{-0.2211} \left(\frac{\ln R}{0.9}\right)^{1/0.4436} + \gamma \quad \text{(Hardened/Tempered)}$$

$$N_n = \left(\frac{S-0.5S_u}{3.4816}\right)^{-2.371} \left(\frac{\ln R}{0.9}\right)^{1/0.4371} + \gamma \quad \text{(Normalized)}$$

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