FATIGUE AND MONOTONIC PROPERTIES OF AN INTERSTITIAL FREE STEEL SHEET

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ABSTRACT

In the present work, the monotonic and low cycle fatigue properties of a thin sheet produced from interstitial free steel containing titanium additions were investigated. Fatigue tests were conducted under deformation control (R_ε=-1) using a grip alignment fixture. The material presented different fatigue behavior for the transverse and longitudinal directions, related to the rolling direction. A comparison between monotonic and cyclic stress-strain curve in the transverse direction showed that the material exhibits cyclic hardening in all tested strain amplitudes. The strain-life relationship was obtained for transverse direction; buckling of longitudinal specimens made impossible to obtain such relationship. Several prediction methods of fatigue properties obtained from monotonic properties were compared to the experimental results and the Four Point Correlation and the Modified Universal Slopes Methods showed a good correlation for the low cycle region.

Keywords - fatigue properties, mechanical properties, IF, interstitial free steel.

INTRODUCTION

Nowadays, the main aim of sheet metal industries is to produce steel sheets as thin as possible, combining high strength and good formability. The Interstitial Free Steel or simply IF Steel is one of such materials showing these features.

In IF steels carbon and nitrogen contents are found to be less than 50 ppm in weight. They are manufactured through vacuum degassing process and generally contain titanium and/or niobium additions that combined to the soluble carbon and nitrogen form precipitates, resulting in a high cold formability [1].

The determination of fatigue properties in such thin sheets is extremely problematic due to the high risk of buckling of the sheet during compression [2,3,4].

Thin sheets are fatigued only under plastic loading. In service, this condition of loading is achieved in regions containing stress concentrators, although the external loading is below the yield strength and the buckling resistance. Therefore, to determine the fatigue properties of thin sheets, unnotched specimens must be submitted to elastic-plastic loading and tests must be conducted under strain control (R_ε=-1) [4]. In order to avoid buckling during alternating tests, it is essential an adequate specimen geometry and also a high precision grip alignment fixture.

The main aim of this work was to determine monotonic and fatigue properties of a Ti-added IF steel. The tests were conducted under strain control (R_ε = -1) and the results were compared to prediction methods.

MATERIALS AND EXPERIMENTAL PROCEDURES

The material consists of a Ti-added IF steel, 1 mm thick, 80% cold rolled and fully annealed. The chemical composition of the steel in wt % is: C 0.0059, Mn 0.144, P 0.016, S 0.0091, Si 0.007, Al 0.044, N 0.0061 and Ti 0.076.

Tensile tests were conducted at room temperature, in a 100kN capacity testing machine at crosshead speed of 0,5 cm/min. The tensile specimens were manufactured and tested according to ASTM E-8 [5], ASTM E-517 [6] and ASTM E-646 [7] standards. The specimens were cut in longitudinal, 45^o and transverse directions related to the rolling direction of the steel.

The geometry of the fatigue specimens is shown in Fig. 1; the thickness of the specimens was 1mm. The axes of the fatigue specimens were parallel and transverse to the rolling direction of sheet steel, and designed to minimize buckling during fatigue tests conducted under negative strain ratio (R_ε=-1).

Grips were carefully aligned with the aid of one MTS alignment fixture. The elongation of the fatigue specimens was measured using an extensometer with gage length of 8,0 mm, which was attached to the specimens using springs The free buckling length between the grips was fixed in 20 mm. The fully reversed strain controlled fatigue tests were performed according to ASTM E-606 [8] standard in air and at room temperature, on a computer controlled servo-hydraulic MTS testing machine with a maximum capacity of 200kN.

A 50% load drop in relation to the cycle of reference was adopted for failure criterion. Total strain amplitudes in the range from 0,15% to 0,45% were used in the testing program. The tests were carried out at frequencies ranging from 0,3Hz to 5Hz with the first load reversal in tension.

The texture of the sheet was determined by means of pole figures generated through X-ray diffraction techniques using a Siemens DSM 5000 diffractometer.

RESULTS AND DISCUSSION

Monotonic Properties:

Table 1 presents the results of monotonic properties for the material in the 3 tested directions of the sheet: L (longitudinal), LT (45^o) e T (transverse).

Transverse specimens showed higher yield strength, ultimate strength, total elongation and normal anisotropy. Longitudinal specimens exhibit higher area reduction, ductility and hardening exponent.

The high normal anisotropy (R_m=2,04) and the low planar anisotropy (ΔR=0,134) result in good formability properties.

Transverse Fatigue Properties:

The elastic, plastic and total strain-life curves for the transverse direction are presented in Fig. 2. In this figure, it can be seen the transition point ($2N_t=1{,}4\times10^5$ reverses) limiting the low and high cycle regions.

The total strain-life relation can be expressed as:

$$\Delta\varepsilon_t/2 = 0{,}0186(2N_f)^{-0{,}262} + 0{,}235(2N_f)^{-0{,}476} \qquad (1)$$

Fig. 3 shows the strain-life curves for IF-Ti (Transverse), a deep drawing quality steel (DDQ)[2] and stainless steel AISI 301 [9]. It can be observed that the DDQ steel exhibits a behavior similar to the observed in the IF-Ti steel. In relation to the AISI 301 steel, IF-Ti steel presents higher lives for the low cycle region and lower lives for the high cycle region. This result was expected, since the stainless steel has higher yield strength (255 MPa) and ultimate strength (849 MPa) than the IF-Ti steel, being more suitable to high cycle fatigue.

Fig. 4 presents the monotonic and cyclic stress-plastic strain curves for the transverse direction. The equations of these curves can be compared below:

$$\sigma = 596{,}0\varepsilon_p^{\,0{,}300} \quad \text{(Monotonic)} \qquad (2)$$

$$\sigma = 190{,}6\varepsilon_p^{\,0{,}0506} \quad \text{(Cyclic)} \qquad (3)$$

According to Mitchell [10], materials with monotonic hardening exponent, n, higher than 0,15 presents cyclic hardening. In fact, from Fig. 4 it can be derived that the IF-Ti steel (n=0,235) exhibited cyclic hardening in all tested strain amplitudes.

Figure 5 presents a comparison of the stress amplitude ($\Delta\sigma/2$) evolution for all strain amplitudes tested. It can be inferred (for strain amplitudes above 0,25%) that the material initially softens, followed by hardening and then softens again until half-life. In the second half of life there is a slight hardening again.

Neuber Factor Analysis:

The Neuber factor $(\Delta\sigma.\Delta\varepsilon.E)^{1/2}$ provides a reliable prediction of the fatigue life of notched components taking into account the local stress-strain fields at the notch, and can be regarded as a damage parameter for notched components if the nominal stress (ΔS) and the fatigue concentration factor (K_f) are known [11]. The Neuber analysis can be summarized by the following relationship:

$$K_f\, \Delta S = (\Delta\sigma.\Delta\varepsilon.E)^{1/2} \tag{4}$$

The product of the nominal stress (ΔS) and the fatigue concentration factor (K_f) defines a hyperbola, where stress versus strain = constant. The intersection of this curve with the cyclic stress-strain curve gives an estimation of the notch root stress and strain. Higher the strength of a steel, lower is the local strain and thus, the cyclic deformation response as well as its fatigue resistance will command notched behavior [11].

Life curves in terms of the Neuber factor can be generated from strain controlled smooth specimens data by extracting the strain range ($\Delta\varepsilon$) and corresponding steady-state stress range ($\Delta\sigma$) for each point. Fatigue lives of notched components can be estimated by entering these curves at the appropriate value of $K_f\, \Delta S$, providing a more realistic indication of the relative performance of materials in actual components.

Fig. 6 shows the Neuber factor-life curves for IF, DP400 [2], DDQ [2] AISI 301[9] and IF-HS180 [12] steels. It can be seen that IF steel presents the lowest Neuber factor.

Buckling of Longitudinal Specimens:

All 14 tests on transverse specimens were successful. However, in 14 attempts of testing longitudinal specimens, 13 resulted in buckling. The explanation for such behavior could be the material anisotropic properties when submitted to fatigue loading in transverse and longitudinal directions.

The material texture analysis using pole figures (Fig. 7) showed two strong texture components: {554}<225> and {111}<112>. Considering both {554}<225> and {111}<112> texture components for the IF-Ti steel and with the knowledge that the major slip systems of body centered cubic metals are composed by the {110}planes and <111> directions, it is possible to establish an analysis of the number of slip systems that may operate during loading in a specific direction. The slip systems that may operate are those, which the Schmid Factor is different from zero.

The Schmid factor is given by $\cos\phi \cos\lambda$ where ϕ is the angle between the load direction and the normal to the slip plane and λ is the angle between the load direction and the slip direction. The higher the Schmid factor the lower the necessary load to activate a slip system. The maximum value of the Schmid factor is 0,5 [13].

Therefore, Table 2 shows the number of slip systems that may operate under transverse and longitudinal loading, considering the two texture components of the IF-Ti steel.

It was possible to verify that during the first cycle, the stress levels achieved for loading in the transverse and longitudinal directions are very similar. However, as the test proceeds, hardening during a longitudinal loading is higher due to the greater number of slip systems that may operate, resulting in a higher degree of dislocation entanglement. Also, the Schmid factor for the majority of these systems are lower than that observed for transverse loading and therefore require higher load to start operating.

As a consequence, during the cyclic loading of longitudinal specimens, the material exhibits a initial hardening that overcomes the buckling resistance of the material for the imposed geometric conditions during the tests. Buckling of longitudinal specimens occurred when compressive stress reached 170 MPa. This value is in accordance with the theoretical value, calculated by the Tangent Modulus Method, described by Shanley [14].

The transverse specimens also exhibit initial hardening for strain amplitudes higher than 0,25%. However, this initial hardening is not enough to overcome the buckling resistance of the material and, consequently, all tests were successful.

Prediction Methods:

Fatigue properties, such as stress-life curve (S-N) and strain-life curve (ε-N), require several and long tests and consequently high costs. Therefore, in the last 35 years, several researchers have developed methods to estimate fatigue properties from monotonic properties [15].

Manson proposed the first methods known as "Four Point Correlation" and "Universal Slopes" to estimate ε-N curves. Socie et al proposed another method adequate for steels called "Socie et al Method" or "Mitchell Method". Muralidharan & Manson proposed the "Modified Universal Slopes Method" and Bäumel & Seeger proposed a new method based in the "Uniform Material Law" [15].

The experimental total strain-life curve is compared to the total strain-life curves estimated by different methods (Fig.8). The Four Point Correlation and the Modified Universal Slopes Methods exhibits better correlation with the experimental curve for the low cycle region than the other methods, which showed to be conservative.

CONCLUSIONS

- The obtained experimental total strain-life equation for transverse direction of IF steel is $\Delta\varepsilon_t/2=0{,}0186(2N_f)^{-0{,}262}+0{,}235(2N_f)^{-0{,}476}$**,** with the transition point at $2N_t=1{,}4x10^5$ reverses.
- Comparison of monotonic stress-strain curve and the cyclic stress-strain curve for the transverse direction indicates cyclic hardening in all tested strain amplitudes.
- The IF steel exhibits the lowest Neuber factor when compared to other automotive sheet steels.
- For strain amplitudes above 0,25%, transverse specimens exhibit initial softening followed by hardening and softening again until half-life. In the second half-life, a slight hardening is observed.
- Longitudinal specimens exhibit a higher initial hardening than transverse specimens due to texture of the material, reaching the buckling resistance. Therefore, it was impossible to test the material in longitudinal direction under the geometrical imposed conditions (sheet thickness and buckling length).
- Four-Point Correlation and the Modified Universal Slopes Methods give better predictions for IF-Ti fatigue properties. However, it seems necessary to formulate an improved prediction method that fits more suitably to the IF steel.

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Table 1
Monotonic properties of IF-Ti steel.

specimen	Yield strength (0,2%)(MPa)	Ultimate Strength (MPa)	Area reduction (%)	Elongation (%)[1]	Ductility	Hardening exponent[2]	Normal anisotropy[3]
L	111.1	287.9	58.2	53.7	0.872	0.251	1.83
LT	116.4	291.4	52.4	51.9	0.742	0.246	1.91
T	124.1	301.1	55.2	55.2	0.803	0.233	2.52
Average	117.2	293.5	55.3	52.7	0.806	0.243	2.04

1- Total elongation in 50mm.
2- Value obtained for the interval 0.2% to 8% .
3- Test interrupted at 20% elongation.

Table 2.
Slip systems and Schmid factor.

{554}<225>		{111}<112>	
Number of slip systems	Schmid Factor	Number of slip systems	Schmid Factor
Longitudinal			
2	0,087	2	0,136
2	0,186	4	0,272
2	0,247	2	0,408
2	0,334		
2	0,433		
Transverse			
4	0,408	4	0,408

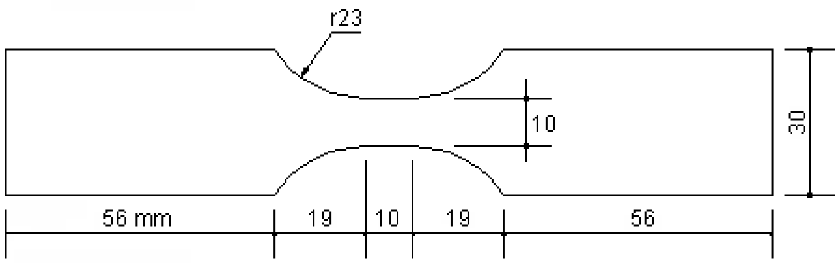

Figure 1: Fatigue specimen (measurements in mm).

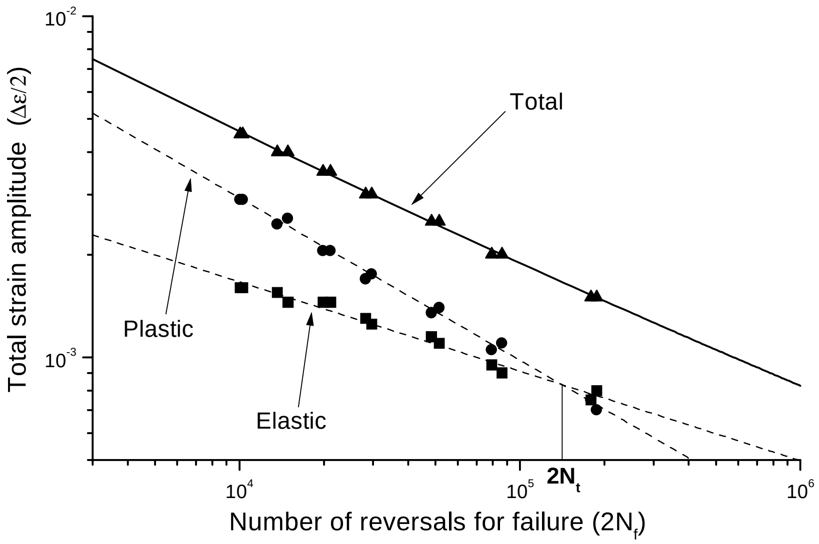

Figure 2: Experimental strain-life curves obtained for transverse direction.

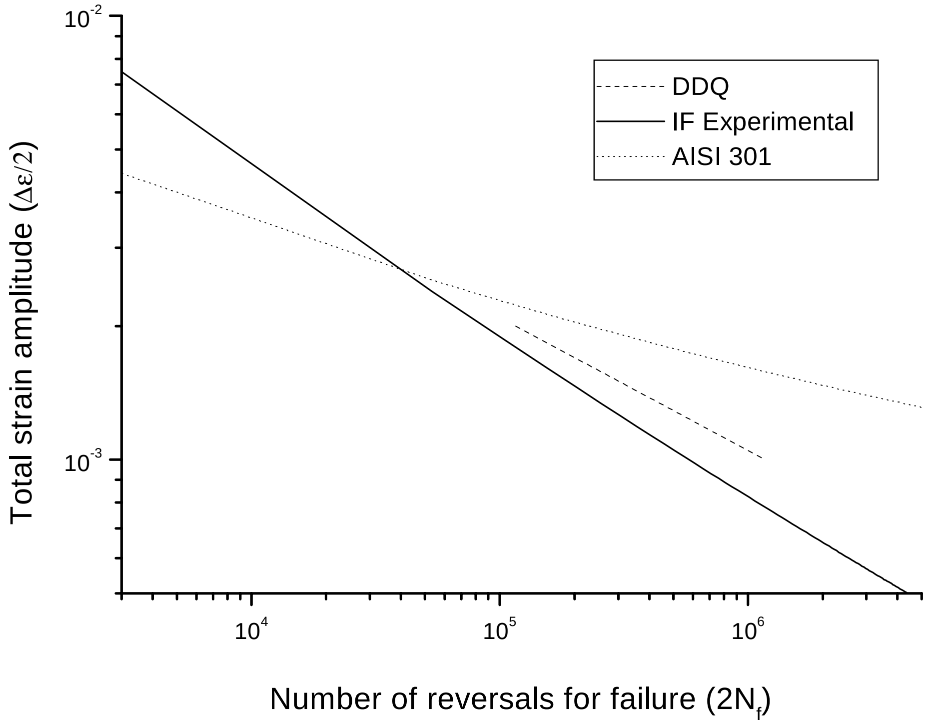

Figure 3: Strain-life curves for IF-Ti (Transverse), DDQ and AISI 301.

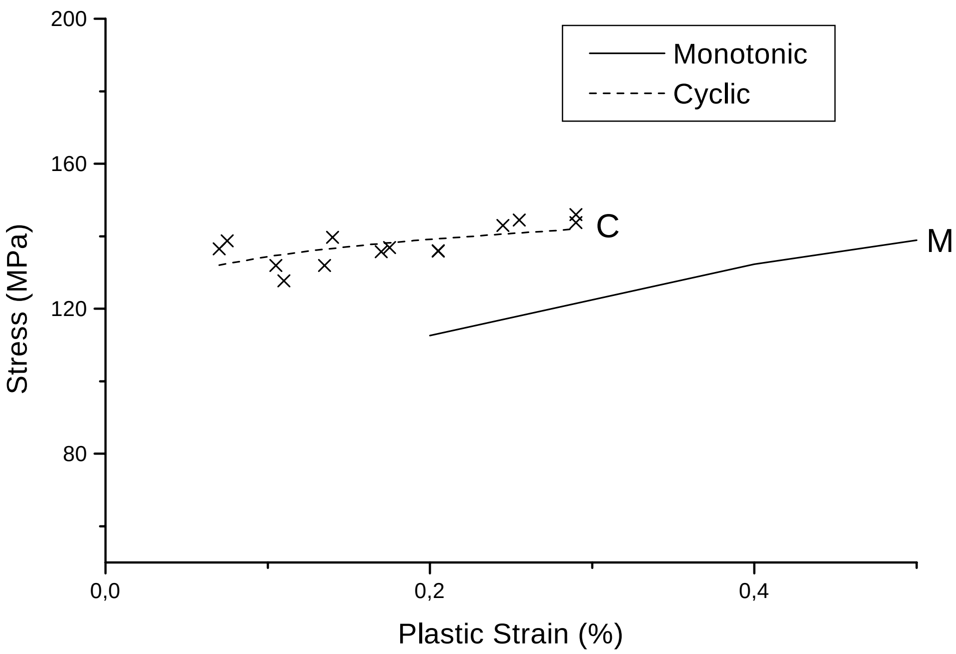

Figure 4: Monotonic and cyclic stress-plastic strain curves.

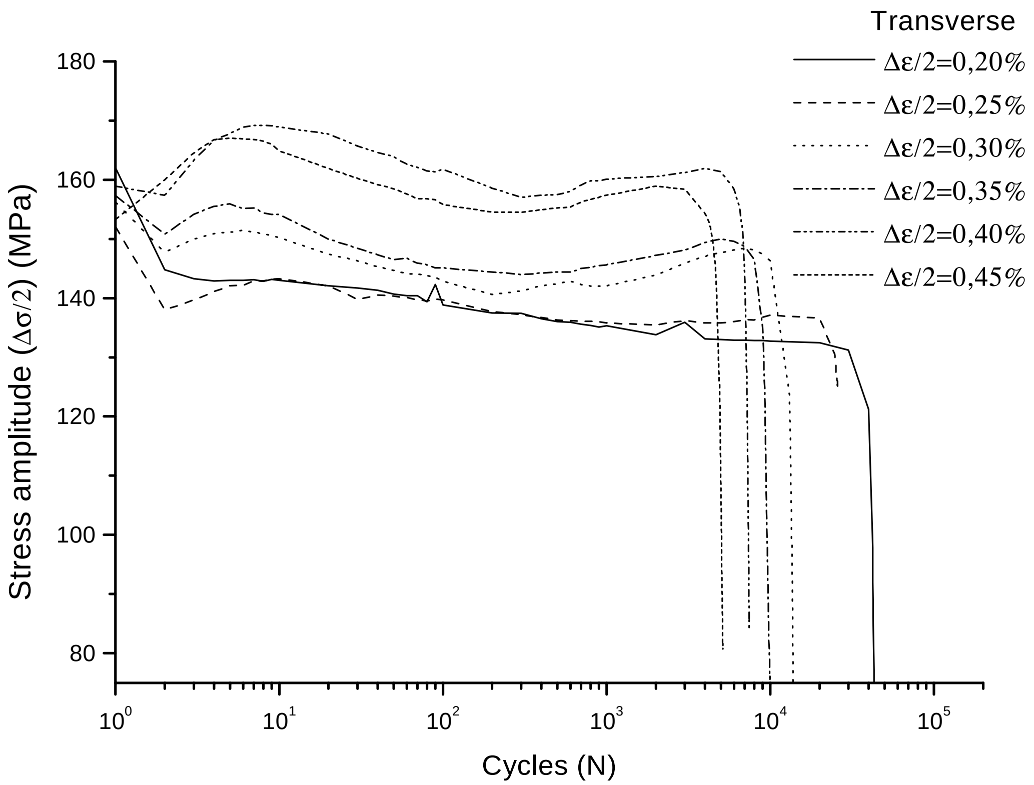

Figure 5: Stress amplitude evolution ($\Delta\sigma/2$) (Transverse).

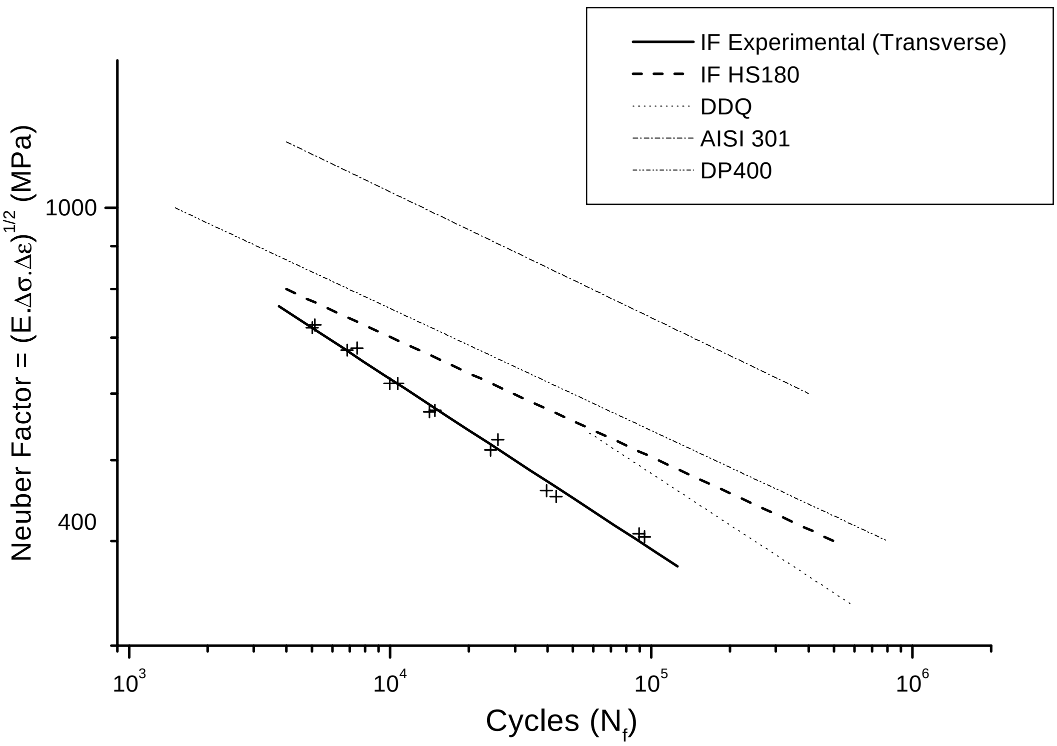

Figure 6: Neuber factor-life curves for automotive steels.

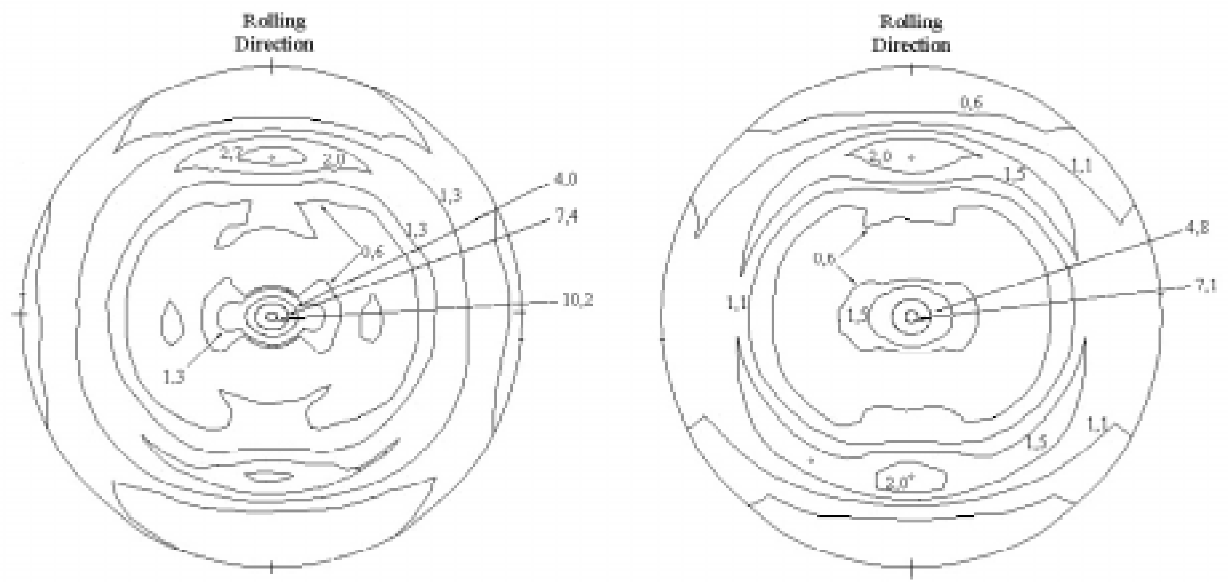

Figure 7: {111} and {554} pole figures, respectively.

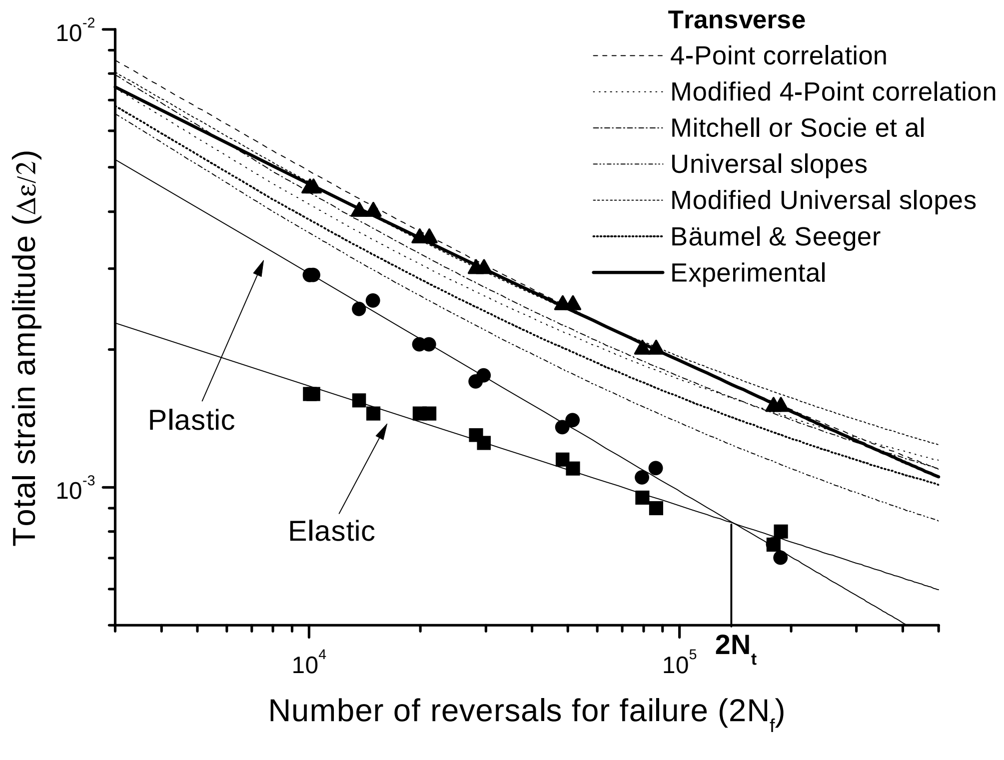

Figure 8: Estimated and experimental total strain-life curves for transverse direction.