Notched multiaxial fatigue of Al7050-T7451: on the need for an equivalent process zone size

M.V.C Sá
Department of Mechanical Engineering, Faculty of Technology, University of Brasília, Brazil
Federal Institute of Brasília, Brasília, Brazil
marcuscsa@gmail.com

J.L.A Ferreira, C.R.M da Silva
[2]*Federal Institute of Brasília, Brasília, Brazil*
jorge@unb.br
cosmeroberto@unb.br

J.A. Araújo
Department of Mechanical Engineering, Faculty of Technology, University of Brasília, Brazil
jaaunb@gmail.com, alex07@unb.br

ABSTRACT. The aim of this work is to investigate stress gradient effects on the fatigue life estimation of notched Al 7050-T7451 specimens under combined torsion and push-pull loading conditions. Initially, simple push-pull and torsion fatigue tests in plain and notched specimens were independently conducted not only to obtain the material properties necessary to calibrate a standard multiaxial critical plane based model, but also to raise the critical distance *versus* life curves in tension ($L_\sigma - N_f$) and in torsion ($L_\tau - N_f$). This latter step also required a Finite Element Elastic Stress Analysis of the notched specimens tested in the medium high-cycle fatigue regime. Then, proportional multiaxial fatigue tests were carried out using this same notched geometry. The combination of a multiaxial model with the theory of critical distance (TCD) was applied to estimate fatigue lives. For this aluminium alloy, neither the use of the $L_\sigma - N_f$ nor $L_\tau - N_f$ combined with the predictive multiaxial model was able to estimate lives in an accurate way.

KEYWORDS. Multiaxial fatigue; Notched fatigue; stress gradient; Process zone; Critical distance; Al 7050-T7451.

OPEN ACCESS

Citation: Sá, M.V.C., Ferreira, J.L.A., Silva, C.R.M., Araujo, J.A., Notched multiaxial fatigue of Al7050-T7451: on the need for an equivalent process zone size, Frattura ed Integrità Strutturale, 41 (2017) 90-97.

Received: 28.02.2017
Accepted: 15.04.2017
Published: 01.07.2017

INTRODUCTION

Aluminium alloys have been used mainly in the aeronautical industry for more than eighty years due to its low density and good mechanical resistance. The Al 7050-T7451 alloy was developed in the 1970´s and has been used not only in the fuselage but also to build structural parts of the wings and landing gears of aircrafts. Despite its technical and economical relevance for such industry, there are few works available in the literature on fatigue of this alloy. Further, most of the research carried out has been concentrated on the effects of shot peening or surface treatments on the fatigue resistance of the material under simple push-pull loadings. For instance, Carvalho and Voorwald [1] investigated the effect of shotpeening and hard Chromium coating on the fatigue resistance of the Al 7050-T7451. They found out that the deleterious effect of such a coating on the fatigue behavior of the alloy was caused by the presence of high tractive residual stresses and micro-cracks, both generated by the electrodeposition process. They also found that this deleterious effect could be mitigated by the use of shot peening. In 2011, Gao [2] tested Al 7050-T7451 specimens subjected to laser peening and conventional shot peening. The obtained results showed that laser peening was more effective to enhance the fatigue resistance than shot peening provoking an increase of 42% in strength when compared to specimens, which were not surface peened. This improvement was of 35% due to shot peening.

Under multiaxial fatigue conditions, as far as the authors are aware, only one article by Chen et al. [3] reported experimental data on Al 7050-T7451. These authors carried out seven different types of tests under axial-torsional variable strain amplitude. They sought to evaluate the accuracy in estimating life of four multiaxial fatigue parameters that did not include any weight factors in their formulation. They concluded that the use of such models provided good fatigue life estimates for this alloy. However, tests were in low cycle fatigue regime and no stress gradient was present. For components operating in the medium or high cycle fatigue regime (MHCF or HCF) the presence of geometric discontinuities is usual. There is a number of multiaxial fatigue criteria available in the literature to estimate fatigue life under more complex stress states [4-7]. The introduction of stress gradient effects caused by notches (or contact mechanics, etc) into such models is still a matter of strong debate among fatigue scientists. An interesting approach to do so is to consider the existence of a critical distance [8-10]. More recently, it has been suggested [11] that a combination of a critical plane based multiaxial model with a simple linear relation between critical distance and life extracted from push-pull data could provide good estimates of life for notched components under multiaxial loading in the MHCF or HCF regime. The purpose of this work is to further investigate this problem. In order to do so, the critical distance against life relation will be raised not only for fully reversed push-pull tests but also for alternated torsion. Both curves will be combined with a critical plane multiaxial fatigue criterion to estimate life. The aim here is to assess the role of combined shear and normal stress gradients in the life methodology. To validate the analysis multiaxial fatigue tests were conducted on notched Al 7050-T7451 specimens.

MULTIAXIAL MODEL AND LIFE DEPENDENT CRITICAL DISTANCE

This work will require que use of a multiaxial fatigue criterion and a method to incorporate the stress gradient effects in the life estimation approach. The multiaxial model considered here is the Modified Wöhler Curve Method (MWCM) [6]. It is based on a diagram where τ_a is plotted against the number of cycles to failure, N_f. This diagram contains different fatigue curves characterized by different values of ρ ratio. ρ is the ratio between the shear stress amplitude, τ_a, and the maximum normal stress, $\sigma_{n,max}$, acting on the material plane experiencing the maximum shear stress amplitude (i.e., the so-called critical plane). Each modified Wöhler curve is defined by its negative inverse slope, κ, and by a reference shear stress amplitude, $\tau_{A,Ref}$, extrapolated at an appropriate number of cycles to failure, N_A. For a given material, the corresponding modified Wöhler diagram can directly be built provided that the κ vs. ρ and $\tau_{A,Ref}$ vs. ρ relationships are calibrated by running at least two sets of basic experiments such as fully reversed push-pull (ρ=1) and torsion (ρ=0) as a function of life. After determining the appropriate material constants (see [6,11] for more details) any intermediate modified Wöhler curve can be obtained. From the specific modified Wöhler curve for the ρ ratio that characterizes the local stress history being assessed, the number of cycles to failure can then be estimated as [11]:

$$N_f = N_A \left[\frac{\tau_{A,Ref}(\rho)}{\tau_a} \right]^{\kappa(\rho)} \tag{1}$$

The value of τ_a is here computed by the Maximum Rectangular Hull (MRH) method. It is based on the combination of shear stress amplitudes associated to mutually orthogonal directions on a material plane, and therefore it is capable to distinguish between the damage caused by proportional and non-proportional shear stress paths. The MRH method is well described elsewhere [7,12,13] and space only preclude us to provide a more detailed explanation about the method. More interested readers are invited to visit such references.
The stress gradient effect is accounted by the Theory of Critical Distances (TCD) [8-11] due to its simplicity. The central idea in the TCD is the definition of an effective stress, based on an averaging procedure over a volume surrounding the stress raiser. Fatigue failure is expected to occur if this effective stress exceeds a reference material fatigue strength. Simplified methods can also be formulated by considering averages over an area or a line (Area and Line Methods, respectively) or the stress at a point located at a critical distance, L, from the stress raiser (Point Method). The Point Method is used in this work. At the medium-cycle fatigue regime, L, depends on the number of cycles to failure, N_f. A power law relationship is used to relate L and N_f, i.e.,

$$L\left(N_f\right) = AN_f^b \qquad (2)$$

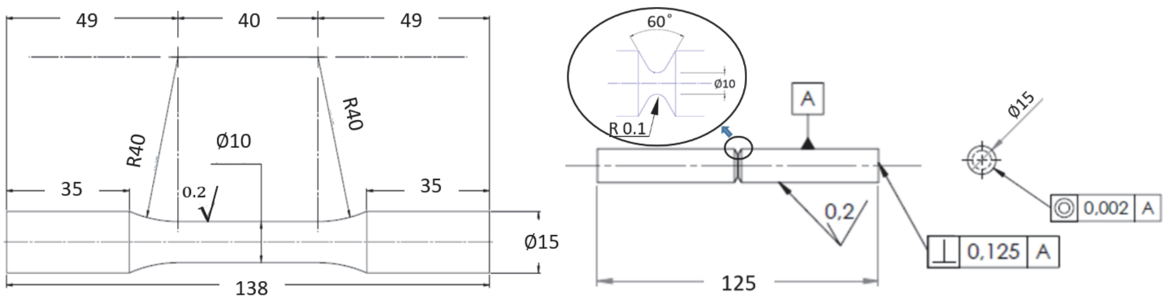
where A and b are material constants. The fitting procedures to obtain these constants require two fatigue curves generated by testing plain and sharply notched specimens. Although such curve has been usually determined for fully reversed push-pull tests ($L_\sigma - N_f$), here we would like to investigate the effect of the torsion mode on the analysis, hence a similar relationship ($L_\tau - N_f$) will be raised from torsion tests of plain and notched specimens too.

MATERIAL AND METHODS

The methodology developed for the aim of this work involves experimental and numerical procedures. In the experimental field, fatigue tests were performed in order to obtain the σ-N and τ-N curves for the plain and the notched specimens, whose geometry and dimensions are shown in Fig. 1 (a) and (b), respectively. All specimens were made of an aluminum alloy 7050 T-7451. Tab. 1 reports the main mechanical properties of the material applied in this research.

Tensile Yield Strength	Ultimate Tensile Strength	Modulus of Elasticity	Poisson´s Ratio
453 [MPa]	513 [MPa]	73 [GPa]	0.33

Table 1: mechanical properties of Al 7050-T7451.



(a) (b)

Figure 1: (a) Plain and (b) notched fatigue specimens.

The plain specimens were designed according to ASTM E 606 standard while the notched ones were designed seeking to achieve the sharpest notch that could be accurately machined and that could satisfy the relation proposed by [14]. This relation requires that the ratio between the radius of the notch root and the net diameter of the notched specimen be smaller than 0.01. In conjunction with the Point Method, this relation allows predictions of ΔK_{th} with an acceptable $\pm 20\%$ error band. The uniaxial fatigue curves were generated according to ASTM E 739 standard. In this way, for each fatigue curve at least four stress amplitude levels were tested covering life ranges from 10^4 up to $2x10^7$ cycles. These tests were then controlled by prescribed loads.

L - N_f curves

To obtain the $L_\sigma - N_f$ and $L_\tau - N_f$ curves (and respective equations) it is necessary to compute the stress field around the notch root. To this aim, a Finite Element Analysis (FEA) was considered. A three dimensional structural element with eight nodes was adopted. Each node had three degrees of freedom. The material behaviour was assumed to be linear elastic. A prescribed stress was applied in the normal direction to simulate the push-pull tests and later a prescribed torsion was applied to model the torsion tests. For a specific failure life, $N_{f,i}$, it is possible to obtain from the experimental curves the respective values of stress amplitude that the unnotched and the notched specimens can withstand, $\sigma_{UN}(N_{f,i})$ and $\sigma_N(N_{f,i})$, respectively. Then, from the FEA, the distance where $\sigma_{UN}(N_{f,i})$ occurs for the notched specimen loaded by a nominal stress $\sigma_N(N_{f,i})$ can be found. Therefore, conducting successive increments in the life cycles, $N_{f,i+1}$, the $L_\sigma - N_f$ is raised. Fig. 2 shows an scheme of this procedure. The $L_\tau - N_f$ curve is obtained following these same steps, but using as a reference the τ-*N* curve.

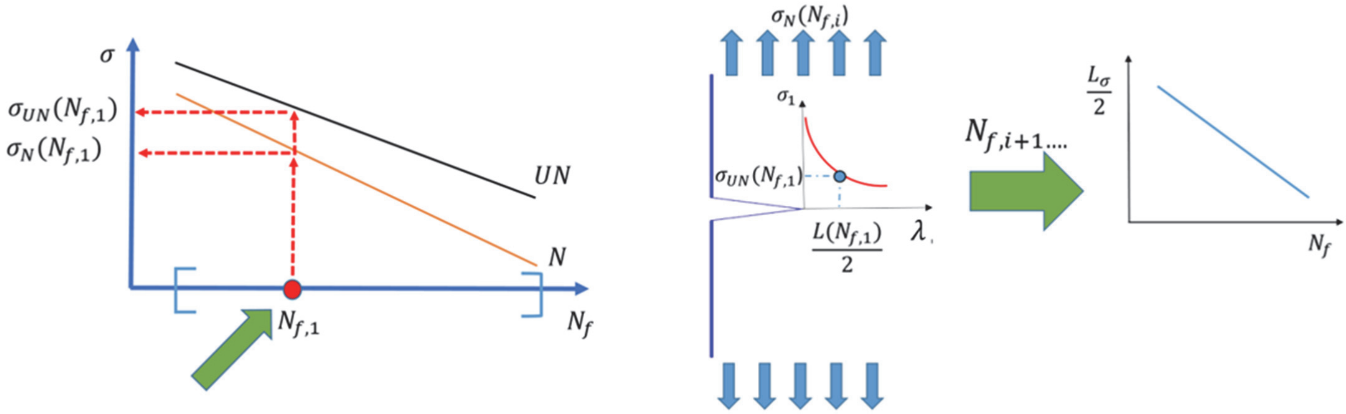


Figure 2: Schematic view of the procedure to obtain the $L_\sigma - N_f$ curve.

Aplication of PM (TDC) and MWCM for life estimation in multiaxial fatigue

The calibration of the Modified Wholer Curve Model (MWCM) can be achieved using the σ-*N* and τ-*N* curves for unnotched specimens. Once calibrated, the amplitude of shear stress at the critical plane, τ_a, at an initial distance from the notch root, λ_i, is the input information for the MWCM and the respective life, $N(\lambda_i)$, is the output. If $L_\sigma(\lambda_i)=\lambda_i$, then $N_f=N(\lambda_i)$.If not, the next increment at the distance λ_i should be sought until convergence is reached. Fig. 3 shows the application of this methodology. This procedure can be repeated but using $L_\tau - N_f$ in conjunction with the MWCM to estimate the life.

To assess the accuracy of the methodology presented above to estimate life of components containing geometrical discontinuities and subjected to complex loadings a set of 15 proportional multiaxial fatigue tests were carried on the notched specimens of Al7050-T7451 shown in Fig. 1. These tests were conducted in a MTS 809 servohydraulic test rig and involved a combination of push-pull and torsion, hence normal load amplitude and torsion amplitude were prescribed to control the tests. The input signals were sinusoidal, synchronous and in phase, without superimposed mean components.

RESULTS

Tests

In Figs. 4(a) and (b) are presented the results of the fatigue uniaxial tests performed under fully reversed push-pull and alternated torsion. These graphs contain then the σ-*N* and τ-*N* curves for the plain and for the notched specimens. In the case of the notched specimens these nominal stresses were computed in terms of the gross sectional area of the specimen.

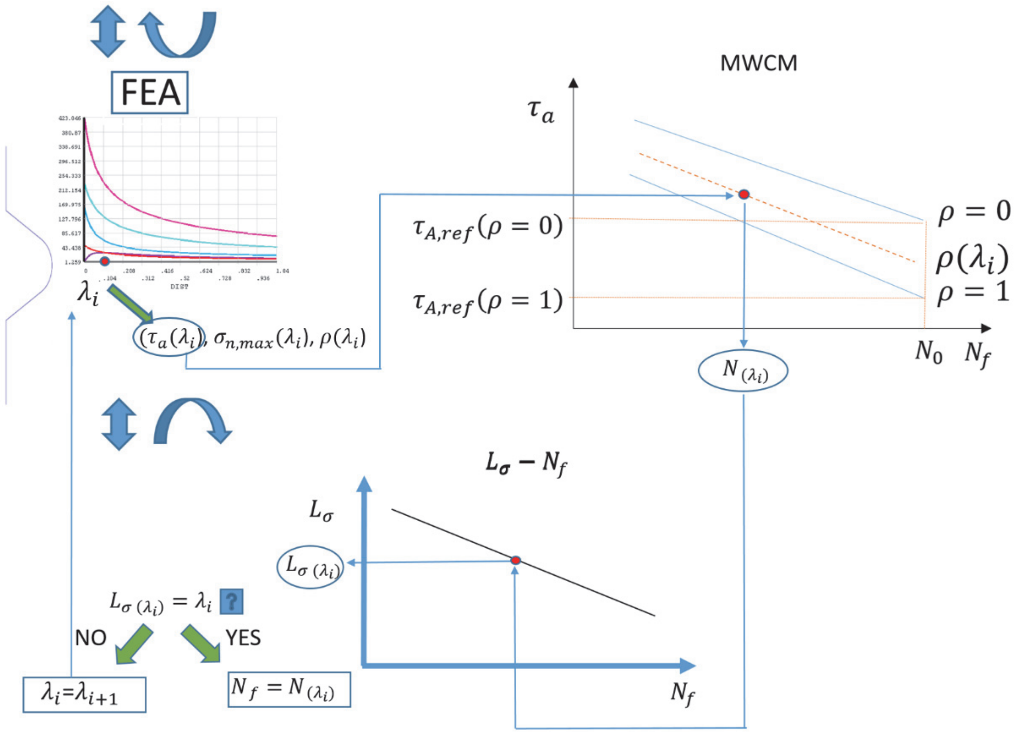


Figure 3: Scheme of the life estimation methodology used in the multiaxial fatigue tests.

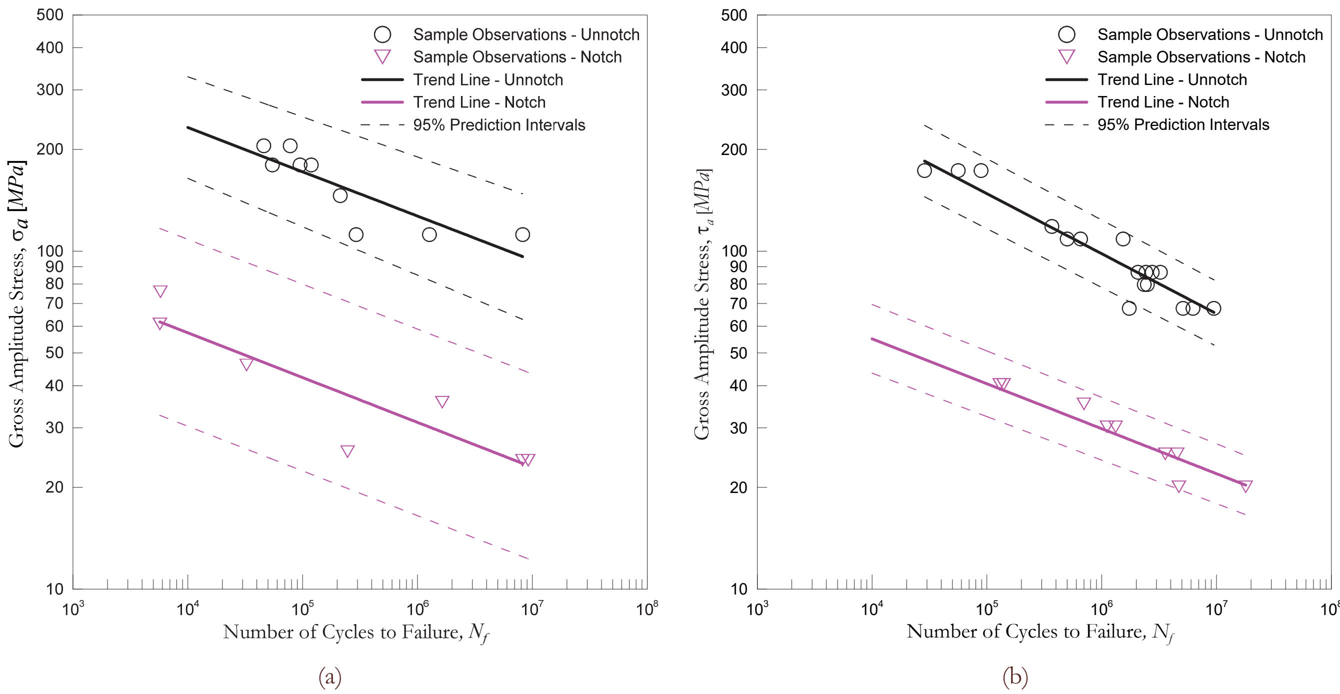


Figure 4: σ-N and τ-N curves of plain and notched specimens performed under fully reversed (a) push-pull and (b) torsion conditions.

The trend line and the scatter bands sketched in these diagrams are characterized by a significance level equal to 95% (it was assumed, by hypothesis, that a log-normal distribution represents the number of cycles to failure). The synthesis of the generated results, carried out according to the above statistical procedure, is summarized in Tab. 2. The endurance limits reported in such a Table were raised based on the parallel projection method (considering a number of cycles for failure equal to 5 x 10^8) and the respective fatigue notch factor, K_f, was evaluated considering the relationship between the endurance limits estimated for the specific specimen type.

Specimen type	Loading Conditions	Number of data	Parameters of the S-N curve A	b	Endurance limit [MPa]	FatigueNotch Factor
Plain	Push-Pull	9	775.80	-0.131	56	1
	Torsional	17	1298.36	-0.187	31	1
V-Notched	Push-Pull	7	194.66	-0.133	14	4.1
	Torsional	9	259.72	-0.155	12	2.7

Table 2: Synthesis of the experimental results generated under push-pull and torsion for plain and V-notched specimens

σ_{Gross} [MPa]	τ_{Gross} [MPa]	$(a)/(b)$	Number of Cycles to Failure Experimental	(L_σ-N_f)	(L_τ-N_f)
(a)	(b)	(c)	(d)	(e)	(f)
11.0	22.0	0.5	5.84E+06	3.66E+05	4.28E+06
11.0	22.0		3.34E+06	3.66E+05	4.28E+06
13.0	26.0		3.28E+05	1.37E+05	1.27E+06
13.0	26.0		7.24E+05	1.37E+05	1.27E+06
16.0	32.0		2.32E+05	4.06E+04	2.82E+05
16.0	32.0		2.42E+05	4.06E+04	2.82E+05
19.0	38.0		3.19E+04	1.47E+04	7.90E+04
19.0	38.0		1.04E+05	1.47E+04	7.90E+04
16.0	20.0	0.8	5.74E+06	1.51E+05	1.74E+06
16.0	20.0		3.45E+06	1.51E+05	1.74E+06
16.0	20.0		4.39E+06	3.60E+05	5.22E+06
18.4	23.0		2.11E+06	3.60E+05	5.22E+06
18.4	23.0		1.76E+06	3.60E+05	5.22E+06
25.6	32.0		1.13E+05	1.90E+04	1.34E+05
25.6	32.0		9.91E+04	1.90E+04	1.34E+05

Table 3: Loading conditions and test results for the multiaxial fatigue data generated from the V-notched specimens

Eqs. 3 and 4 below provide the $L_\sigma - N_f$ and $L_\tau - N_f$ relations and were extracted using the methodology schematically shown in Fig. 2. Tab. 3 reports the loading conditions and experimental results generated for the multiaxial fatigue tests with the notched specimens. The experimental program considered two ratios between the normal and shear nominal stress amplitudes (column c, in Tab. 3), i.e, 0.5 and 0.8. Eight tests were conducted using the first ratio and seven for the latter one. The actual lives are reported in column d of Tab. 3. The estimated lives either considering eq. (3), $L_\sigma - N_f$ curve, or eq. (4), $L_\tau - N_f$ relation, in association with the multiaxial model (eq. (1)) are presented in columns e and f, respectively. Graphically, the quality of the results of such estimates can be assessed by plotting the actual lives against the predicted ones, as shown in Fig. 5. In such graph, the continuous lines parallel to the one passing through the origin and the dashed lines represent bandwiths by factors of 2 and 4, respectively. One can see in Fig. 5 that when the $L_\sigma - N_f$ curve was used the estimated lives were excessively conservative. Note that 11 out of the 15 points plotted for this case were out of the factor of 4 bandwith, while the other 4 points fell between the factor of 2 and 4 lines. Although an improvement in the predictions was clearly obtained when the $L_\tau - N_f$ relation was used, still 4 of the 15 points provided non-conservative life estimates by factors between 2 and 4.

$$L_\sigma\left(N_f\right) = 0.2041 N_f^{-0.00314} \tag{3}$$

$$L_\tau\left(N_f\right) = 0.1784 N_f^{+0.06359} \tag{4}$$

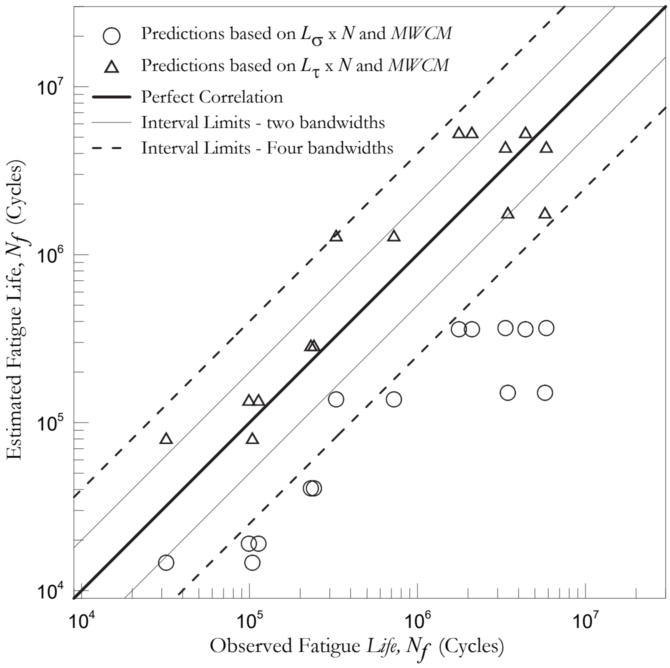


Figure 5: Observed versus estimated lives based on the use of the $L_\sigma - N_f$ and $L_\tau - N_f$.

Conclusions

In this work a set of experimental fatigue data was produced for plain and notched specimens of Al7050-T7451 under uniaxial and multiaxial proportional loading conditions. A methodology available in the literature, which combines a multiaxial critical plane criterion with a critical distance approach was used to estimate the life for the multiaxial tests. Two curves of critical distance against life obtained under uniaxial and torsional loading were considered in order to determine the material point positon from the notch root where the multiaxial model should be computed. The results showed that neither the distance given by the $L_\sigma - N_f$ diagram nor the one given by $L_\tau - N_f$ curve combined with the MWCM model was capable to estimate lives within a reasonable degree of accuracy. While the methodology provided significant conservative life estimates for all data analysed when the distance from the notch root was taken from the $L_\sigma - N_f$ curve, non-conservative predictions up to a factor of four were obtained when such a distance was taken from the $L_\tau - N_f$ diagram. The authors believe that a and equivalent critical distance that could take into account the sensitiveness of the stress gradient produced by the shear and by the normal stress modes could enhance the life estimates. Other multiaxial fatigue criteria should also be investigated and more data, preferably under non-proportional loading, should be used to corroborate the analysis. Future work by the authors will tackle these issues.

Acknowledgements

The authors would like to acknowledge the financial support of ATE II, ATE III, TAESA, TBE, EATE, BRASNORTE, AETE, TME, FINATEC, and CNPq (309748/2013-5).

References

[1] Gao, Y. K., Improvement of fatigue property in 7050–T7451 aluminum alloy by laser peening and shot peening. Materials Science and Engineering: A, 528(10) (2011) 3823-3828.

[2] Carvalho, A. L. M., Voorwald, H. J. C., Influence of shot peening and hard chromium electroplating on the fatigue strength of 7050-T7451 aluminum alloy. International Journal of Fatigue, 29(7) (2007) 1282-1291.
[3] Chen, H., Shang, D. G., Tian, Y. J., Liu, J. Z., Comparison of multiaxial fatigue damage models under variable amplitude loading. Journal of Mechanical Science and Technology, 26(11) (2012) 3439-3446.
[4] Socie, D.F., Marquis, G.B., Multiaxial fatigue. SAE International, (2000).
[5] Carpinteri, A., Spagnoli, A., Vantadori, S., Bagni, C. Structural integrity assessment of metallic components under multiaxial fatigue: the C-S criterion and its evolution. Fatigue Fract Engng Mater Struct, 36 (2013) 870–83.
[6] Lazzarin P, Susmel L, A stress-based method to predict lifetime under multiaxial fatigue loadings. Fatigue Fract Eng Mater Struct, 26 (2003) 1171–187.
[7] Mamiya EN, Castro FC, Araújo JA. Recent developments on multiaxial fatigue: The contribution of the University of Brasília. Theor Appl Fract Mech, 73 (2014) 48–59.
[8] Taylor, D., Geometrical effects in fatigue: a unifying theoretical model. Int J Fatigue, 21 (1999) 413–20.
[9] Susmel, L., A unifying approach to estimate the high-cycle fatigue strength of notched components subjected to both uniaxial and multiaxial cyclic loadings. Fatigue Fract Engng Mater Struct, 27 (2004) 391–411.
[10] Carpinteri, A., Spagnoli, A., Vantadori, S., Viappiani, D., A multiaxial criterion for notch high-cycle fatigue using a critical-point method. Eng Fract Mech, 75 (2008) 1864–74.
[11] Susmel, L., Taylor, D., A critical distance/plane method to estimate finite life of notched components under variable amplitude uniaxial/multiaxial fatigue loading. Int J Fatigue, 38 (2012) 7–24.
[12] Araújo, J.A., Dantas, A.P., Castro, F.C., Mamiya, E.N., Ferreira, J.L.A. On the characterization of the critical plane with a simple and fast alternative measure of the shear stress amplitude in multiaxial fatigue. Int J Fatigue, 33 (2011) 1092–100.
[13] Araújo, J.A., Carpinteri, A., Ronchei, C., Spagnoli, A., Vantadori, S., An alternative definition of the shear stress amplitude based on the Maximum Rectangular Hull method and application to the C-S (Carpinteri-Spagnoli) criterion. Fatigue Fract Engng Mater Struct, 37 (2014) 764–71.
[14] Da Silva, B.L., Ferreira, J.L.A., Araújo, J.A., Influence of notch geometry on the estimation of the stress intensity factor threshold by considering the Theory of Critical Distances, International Journal of Fatigue, 42 (2012) 258-270.