Effect of numerical parameters on plastic CTOD

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ABSTRACT. Fatigue crack growth (FCG) is associated with irreversible and non-linear processes happening at the crack tip. This explains different problems observed in the use of da/dN-ΔK curves, namely the inability to explain stress ratio and load history effects. The replacement of ΔK by non-linear crack tip parameters, namely the crack tip opening displacement (CTOD) is an interesting alternative. However, the determination of CTOD, using the finite element method, depends on different numerical parameters, not sufficiently studied so far. The objective here is to study the effect of these parameters on plastic CTOD, and therefore on da/dN-$\Delta CTOD_p$ curves. A transient behaviour was found at the beginning of numerical crack propagation which is linked to the formation of residual plastic wake. Therefore, a minimum number of crack increments is required to obtain stabilized values. On the other hand, the predicted $\Delta CTOD_p$ decreases with the distance to crack tip. Close to the crack tip, sensitivity to the measured values is much higher, but it also exists at remote positions. In addition, the mesh has a relatively low influence on $\Delta CTOD_p$. Finally, the effect of the number of load cycles between crack increments greatly depends on material properties.

KEYWORDS. Crack tip opening displacement (CTOD); Plastic CTOD; Finite element method; Numerical parameters.

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INTRODUCTION

The analysis of fatigue crack propagation is usually conducted by relating the crack advance per unit cycle, da/dN, to the stress intensity factor range, ΔK. Nevertheless, da/dN-ΔK relations have several limitations, namely: (i) such curves are completely phenomenological, not derived from physics, and the fitting parameters have units with no physical justification; (ii) such curves are only valid in the small-scale yielding range; (iii) and da/dN depends on other parameters, including the stress ratio and the load history. In order to overcome the difficulties related to the application of K to the analysis of fatigue crack growth, several concepts have been proposed, namely crack closure, partial crack closure, T-stress or the CJP model. In authors' opinion, the linear elastic ΔK parameter must be replaced by non-linear crack tip parameters, because fatigue crack growth is effectively linked to non-linear processes happening at the crack tip. Different parameters have been proposed to quantify crack tip plastic deformation, namely the plastic strain range, the energy dissipated around the crack tip and the crack opening displacement (COD) [1]. The crack opening displacement (COD) is a classical parameter in elastic-plastic fracture mechanics, still widely used nowadays [2]. It has also great importance for fatigue analysis. Crack tip blunting under maximum load and re-sharpening of the crack-tip under minimum load were used to explain fatigue crack growth under cyclic loading [3]. Additionally, it was shown by various authors that there is a relationship between the striation spacing (related to the amplitude of crack tip blunting over a full fatigue cycle) and the crack growth rate [4]. The experimental measurement of COD is usually made remotely to crack tip. In CT specimens an extensometer with blades is used to measure the opening of the specimen at the edge, usually called crack mouth opening displacement (CMOD). In the M(T) specimen a pin extensometer is placed at the center of the specimen, fixed in two small holes to avoid sliding. However, optical techniques have been gaining increased relevance. Nevertheless, the crack tip opening displacement, CTOD, has only been measured numerically or analytically. In the finite element analysis, the displacement of the first node behind the crack tip is generally used as an operational CTOD [5]. The crack profiles also express the crack opening displacements, and are interesting to analyze the effect of load history.

In a previous work [6], da/dN was related with the range of plastic CTOD, $\Delta CTOD_p$, for the 7050-T6 aluminum alloy. It was found to be a viable and interesting alternative to ΔK, since it is a local parameter that quantifies crack tip plastic deformation, which is expected to control fatigue crack growth. Additionally, it includes naturally the effect of crack closure and fatigue threshold. The relation between the numerical $\Delta CTOD_p$ and the experimental da/dN values was used to predict fatigue crack growth rates for other loading conditions. The $\Delta CTOD_p$ was predicted numerically at the first node behind crack tip, at a distance of 8 μm from it. However, there are several numerical parameters which may affect by the magnitude of plastic CTOD, and therefore of da/dN versus $\Delta CTOD_p$ relations. The objective here is to study the effect of these parameters on $\Delta CTOD_p$, namely the measurement node behind crack tip, the crack propagation, the finite element mesh, and the number of load cycles between crack increments.

NUMERICAL MODEL

The specimen geometry studied was a Middle-Tension specimen, having W=60 mm, and a small thickness (t=0.2 mm) in order to obtain a plane stress state. A straight crack was modeled, with an initial size, a_o, of 5 mm (a_o/W=0.083). Since the specimen is symmetric about three orthogonal planes, only 1/8 was simulated considering proper boundary conditions. Pure plane strain state was also modeled constraining out-of-plane deformation. The materials considered in this research were the 6016-T4 (σ_{ys}=124 MPa) and 6082-T6 (σ_{ys}=238 MPa) aluminum alloys. The mechanical behaviour was represented using an isotropic hardening model described by a Voce type equation:

$$Y = \sigma_{\mathrm{ys}} + R_{sat}(1 - e^{-n_v \bar{\varepsilon}^{\mathrm{p}}}) \tag{1}$$

combined with a non-linear kinematic hardening model described by a saturation law:

$$\dot{\mathbf{X}} = C_x \left[X_{sat} \frac{(\boldsymbol{\sigma}' - \mathbf{X})}{\bar{\sigma}} - \mathbf{X} \right] \dot{\bar{\varepsilon}}^{\mathrm{p}},\ \mathbf{X}(0) = \mathbf{0} \tag{2}$$

In the previous equations, Y is the flow stress, $\bar{\varepsilon}^{\mathrm{p}}$ is the equivalent plastic strain, σ_{ys} is the initial yield stress, R_{sat} is the saturation stress, n_v, C_x and X_{sat} are material constants, $\boldsymbol{\sigma}'$ is the deviatoric stress tensor, X is the back stress tensor, and $\dot{\bar{\varepsilon}}^{\mathrm{p}}$ is the equivalent plastic strain rate. An anisotropic yield criterion, defined by a quadratic function, was considered:

$$F\left(\Sigma_{yy} - \Sigma_{zz}\right)^2 + G\left(\Sigma_{zz} - \Sigma_{xx}\right)^2 + H\left(\Sigma_{xx} - \Sigma_{yy}\right)^2 + 2L\Sigma_{yz}{}^2 + 2M\Sigma_{zx}{}^2 + 2N\Sigma_{xy}{}^2 = \bar{\sigma}^2 \tag{3}$$

where Σ_{xx}, Σ_{yy}, Σ_{zz}, Σ_{xy}, Σ_{xz} and Σ_{yz} are the components of the effective stress tensor ($\mathbf{\Sigma} = \boldsymbol{\sigma}' - \mathbf{X}$) defined in the orthotropic frame; and F=0.5998, G=0.5862, H=0.4138, L=1.2654, M=1.2654, and N=1.2654 are the coefficients that characterize the material orthotropic behaviour. The material constants, determined for 6016-T4 aluminium alloy, are: σ_{ys} =124 MPa, R_{sat}=291 MPa, n_v= 9.5, C_x= 146.5 and X_{sat}= 34.90 MPa. For the 6082-T6 aluminium alloy, the material constants obtained were Y_0 = 238.15 MPa, R_{sat} = 249.37 MPa, n= 0.01, C_X = 244.44, and X_{sat} = 83.18 MPa.

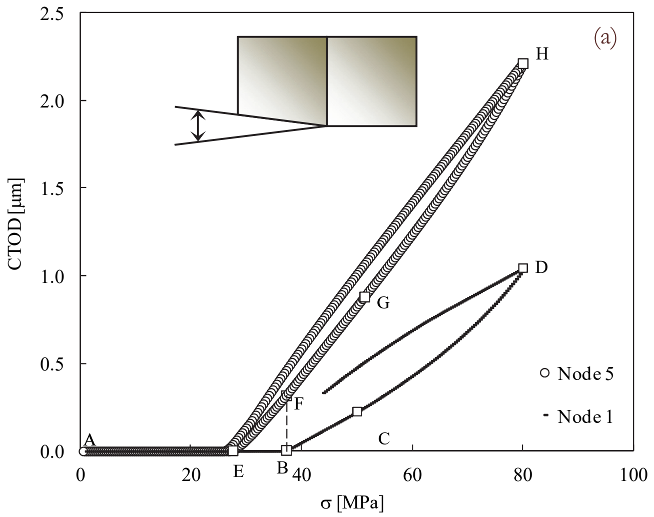
The finite element model of the M(T) specimen had a total number of 6639 linear isoparametric elements and 13586 nodes. The finite element mesh was refined near the crack tip, having 8×8 μm² elements there. Only one layer of elements was considered along the thickness. Crack propagation was simulated by successive debonding of nodes at minimum load. Each crack increment corresponded to one finite element and two load cycles were applied between increments. In each cycle, the crack propagated uniformly over the thickness by releasing both current crack front nodes. A total number of 320 load cycles were applied, corresponding to a total crack propagation of Δa=(160-1)×8 μm=1272 μm. Note that the first two load cycles were applied without crack increment, i.e., at a=5 mm. A wide range of constant amplitude tests was considered. The remote stresses can be obtained by dividing the loads by the area of cross section, i.e., σ=F/A, being A=30×0.1 mm². The numerical simulations were performed with the Three-Dimensional Elasto-plastic Finite Element program (DD3IMP). This software was originally developed to model deep drawing, and was adapted to study PICC due to its great competence in the modeling of plastic deformation. The CTOD was measured at the first node behind crack tip, i.e., 8 μm from crack tip. Further details of the numerical procedure may be found in previous publications of the authors [1,6].

NUMERICAL RESULTS

Effect of measurement point

Fig. 1a presents typical results of CTOD versus load. The CTOD was measured after 160 crack propagations (Δa=1.272 mm), at nodes 1 and 5 behind crack tip. The load is quantified by the remote stress. The first node behind crack tip (node 1) is closed at minimum load (A) and only opens when the load reaches point B, which is the crack opening load. After opening, CTOD increases linearly with load, but after point C, there is some deviation from linearity, which indicates the occurrence of plastic deformation. The maximum CTOD occurs at point D, which corresponds to the maximum applied load. The fifth node behind crack tip (node 5) has higher levels of CTOD as could be expected. The crack opens at point E, at a load lower than observed for node 1. In fact, the crack opens progressively, therefore node 1 is the last node to open. In the region E-F, the crack opens progressively from node 5 to node 1, and only after point E it is totally open. After the opening of node 1 there is a second linear region, but with a slope higher than in region EF, which indicates a lower rigidity. The plastic deformation starts at point G, increasing progressively up to the maximum load (H). After the maximum load, there is also a linear variation of CTOD with load decrease. With subsequent load decrease, reversed plastic deformation starts and the crack closes again. Matos and Nowell [7] studied nodes 1 and 2 behind crack tip. The displacements obtained at node 2 were higher than those obtained with node 1, as could be expected. The same global aspect was observed, however the plastic deformation obtained by them is significantly higher, since the elastic regimes are relatively short. They studied the Ti-6AL-4V titanium alloy, assuming an elastic perfect plastic behaviour, and used 5 or 10 μm elements near the crack tip. However, only the plastic variation of CTOD is relevant for the study of fatigue crack propagation, since this phenomenon is linked to irreversible mechanisms. Fig. 1b plots the variation of $CTOD_p$ for different nodes behind crack tip. For each node, there is a progressive increase of plastic CTOD up to the maximum load. The maximum $CTOD_p$ decreases with the departure of measurement point from crack tip. The load corresponding to the onset of plastic deformation can be used to calculate the fatigue threshold. As can be seen in Fig. 1b, the same fatigue threshold is obtained at different measurement points behind crack tip.

Fig. 2 presents the variation of plastic CTOD range with distance to crack tip, d. There is a sharp decrease of $\Delta CTOD_p$ immediately behind crack tip. This variation is particularly relevant up to a distance of 100 μm behind crack tip. The increase of *d* reduces the rate of variation, however, a slight decrease is always observed, at least for the range of *d* values studied. Note also that there is a great difference between the first value, obtained at a distance of 8 μm behind crack tip ($\Delta CTOD_p$=0.35 μm), and the value measured at a distance of 640 μm behind crack tip ($\Delta CTOD_p$=0.086 μm). In other words, and predictably, the numerical predictions of $\Delta CTOD_p$ are quite sensitive to the position of measurement point relatively to the crack tip.



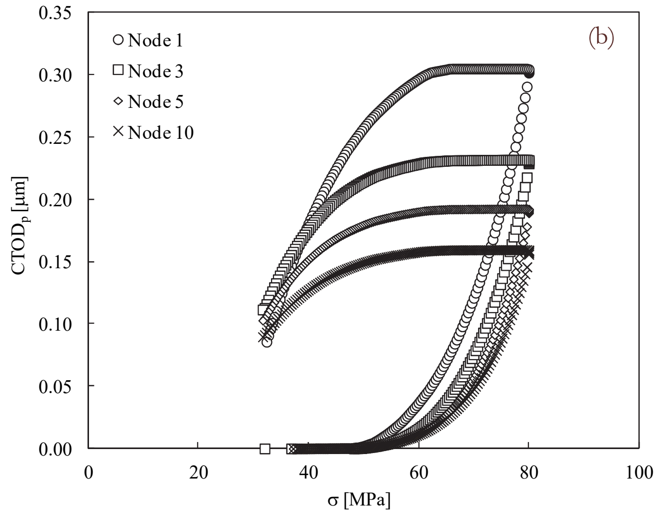


Figure 1: (a) CTOD versus load. (b) Plastic CTOD versus load (6082-T6 AA; plane stress).

An additional measurement was made at the center of the M(T) specimen, which replicates the experimental measurement made with a pin extensometer. The measurement point has coordinates: x=0, y= 1.75 mm. Therefore, it is at a distance of 6.5 mm from the crack tip (x=6.272 mm, y=0). The corresponding values of $\Delta CTOD_p$ are significantly lower than those obtained at a distance less than 1 mm from crack tip. This seems to indicate that sensitivity relatively to the measurement point always decrease with distance d. Anyway, the measurement at a quite remote position is able to capture some plastic deformation, which is remarkable. Similar trends were obtained for all the other loads and materials studied. The same trend was also obtained for plane strain state. Note that the values of $\Delta CTOD_p$ presented are relatively small, lower than 1 µm. This is certainly a challenge for the experimental determination of plastic CTOD.

Effect of crack propagation

In the numerical simulation of FCG, there is a transient behaviour at the beginning of crack propagation. In fact, some crack propagation is required to stabilize the plastic deformation at the crack tip. Fig. 3a presents the variation of $\Delta CTOD_p$ with crack increment, Δa. The first values are relatively high, which can be explained by the low hardening of the material and by the relatively low values of crack closure. Initially the material is virgin in terms of plastic deformation, and, as could be expected, predictions tend to stabilize, as the crack propagates. As can be seen in Fig. 3a, a propagation Δa=552 µm, which corresponds to 70 crack increments of 8 µm, is enough to stabilize the predictions of $\Delta CTOD_p$. After stabilization there is a progressive increase of plastic CTOD with crack propagation, because since the tests are made at constant load, there is a progressive increase of ΔK at the crack tip. For all load cases studied, 100 crack increments were found enough to stabilize the values, however 160 propagations were considered. The distance for stabilization increases with load range.

Fig. 3b shows, in the 7050-T6 aluminum alloy, the effect of stress state on $\Delta CTOD_p$ versus Δa plots. The general behavior is similar for plane stress and plane strain states. In both cases there is an initial decrease, which is more relevant for the plane stress state. The stabilization is relatively fast, compared with that observed in Fig. 3a for the AA6082-T6. After stabilization, there is a relatively fast increase of $\Delta CTOD_p$ with Δa, particularly for plane strain state. The comparison between Figs. 3a and 3b shows the importance of material behavior on the crack tip plastic deformation, here quantified by the plastic CTOD. The analysis of the CTOD versus load plots showed that the 7050-T6 aluminum alloy has no crack closure.

Effect of finite element mesh

The finite element mesh is a main parameter in finite element analyses. Fig. 4 shows the effect of the size of crack tip elements on the predictions of plastic CTOD. There is a relatively low influence of finite element mesh on plastic CTOD. This difference vanishes when the measurement point is relatively far from crack tip. This seems to indicate that the predictions are robust relatively to the finite element mesh. Anyway, if the $\Delta CTOD_p$ is measured at the first node behind crack tip, the value measured using a mesh of 32 μm is lower than that predicted with 8 μm, simply because the first node is more distant.

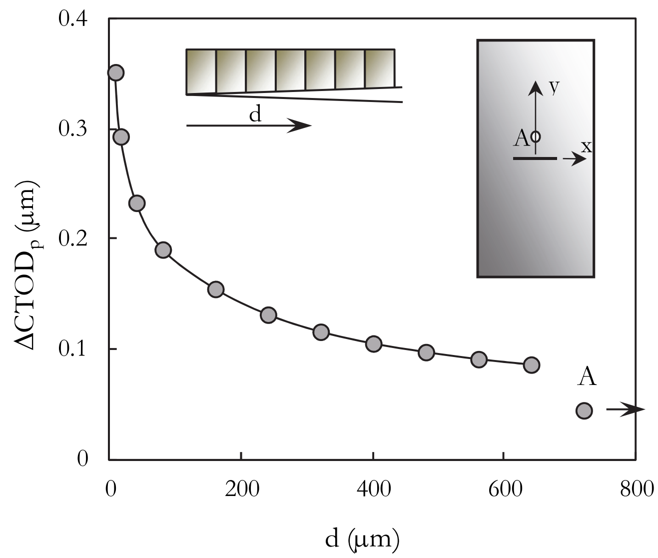


Figure 2: Plastic CTOD range versus distance behind crack tip, d (MT specimen; a=6.272 mm; 6082-T6 AA; mesh M8; contact; plane stress; F_{min}=-40 N, F_{max}=240 N).

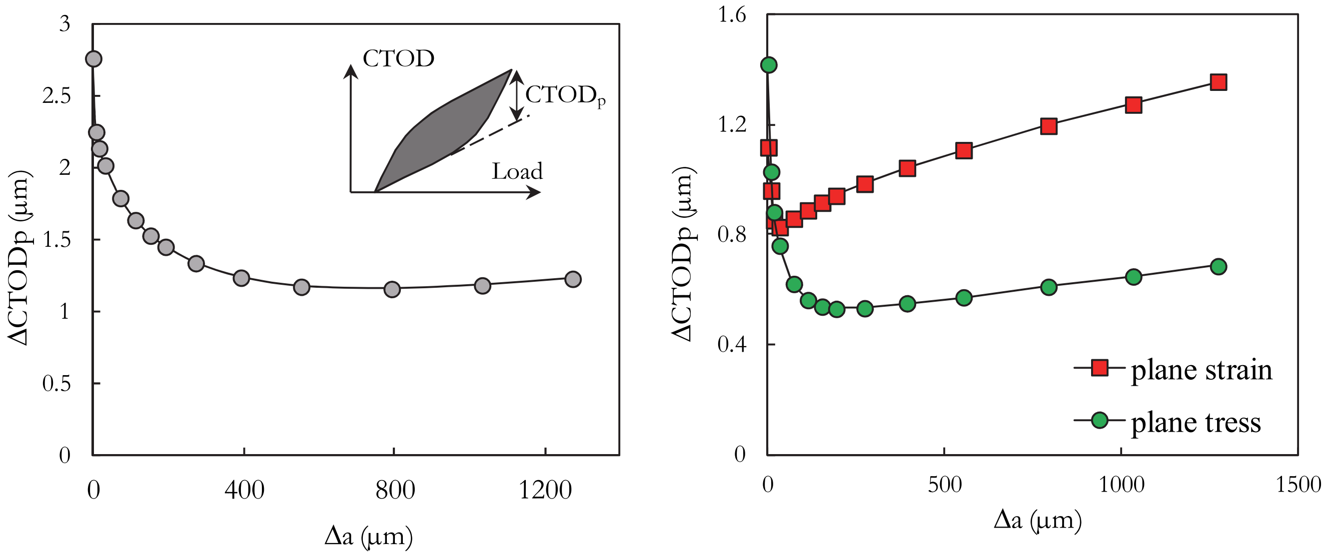


Figure 3: (a) Effect of crack propagation on $\Delta CTOD_p$ (AA6082-T6; node 1; plane stress; F_{min}=0 N, F_{max}=360 N). (b) Effect of stress state (AA7050-T6 F_{min}=165 N, F_{max}=552 N).

Effect of the number of load cycles between crack increments

The number of load cycles between crack increments (NLC) is another major parameter. The application of five load cycles between crack increments is closer to real fatigue crack growth rates than when are used two load cycles. Figs. 5a and 5b present results for the 6082-T6 and 6016-T4, respectively. As can be seen, there is a great difference of behaviour, which indicates that material properties play a major role when the number of load cycles is being studied. In the 6016-T4 the increase of the number of load cycles decreases the values of $\Delta CTOD_p$.

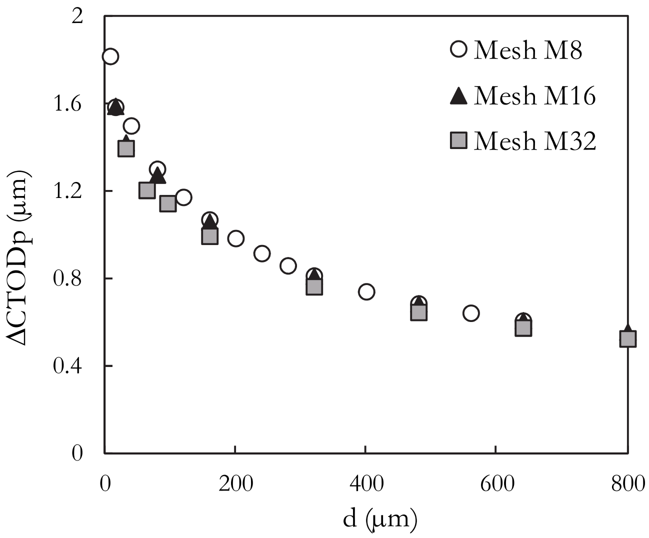


Figure 4: Effect of finite element mesh (AA6082-T6; plane stress; F_{min}=0 N, F_{max}=400 N).

Impact on da/dN predictions

The effect of the measurement node on da/dN predictions was also studied. First, for the AA 7050-T6, two plots of da/dN versus $\Delta CTOD_p$ were obtained using nodes 1 and 12 behind crack tip, at distances of 8 and 96 μm, respectively. In addition, experimental values of da/dN in M(T) specimens were obtained, as described by Antunes *et al.* [6]. Fig. 6a shows linear plots of the da/dN-$\Delta CTOD_p$ values as well as models fitted to the results. Node 12 gives lower values of plastic CTOD, therefore the curves are on the left side of those obtained with node 1, since da/dN is the same. The models presented in Fig. 6a were used to predict the effect of an overload. A numerical analysis was developed for constant amplitude loading with F_{min}=209 N and F_{max}=418 N. In a second analysis, an overload F_{OL}=627 N was applied after 80 crack increments. The plastic CTOD was predicted numerically and was used to obtain the da/dN values using the models defined in Fig. 6a. The results are presented in Fig. 6b. The overload cycle produces a sudden increase of da/dN, followed by an important decrease to a minimum value, and, then, there is a progressive increase to the constant amplitude curves. The global aspect of these predictions are according experimental results [8]. However, in sum, the node behind crack tip used to develop this study is relevant, since different results are obtained, particularly for constant amplitude tests.

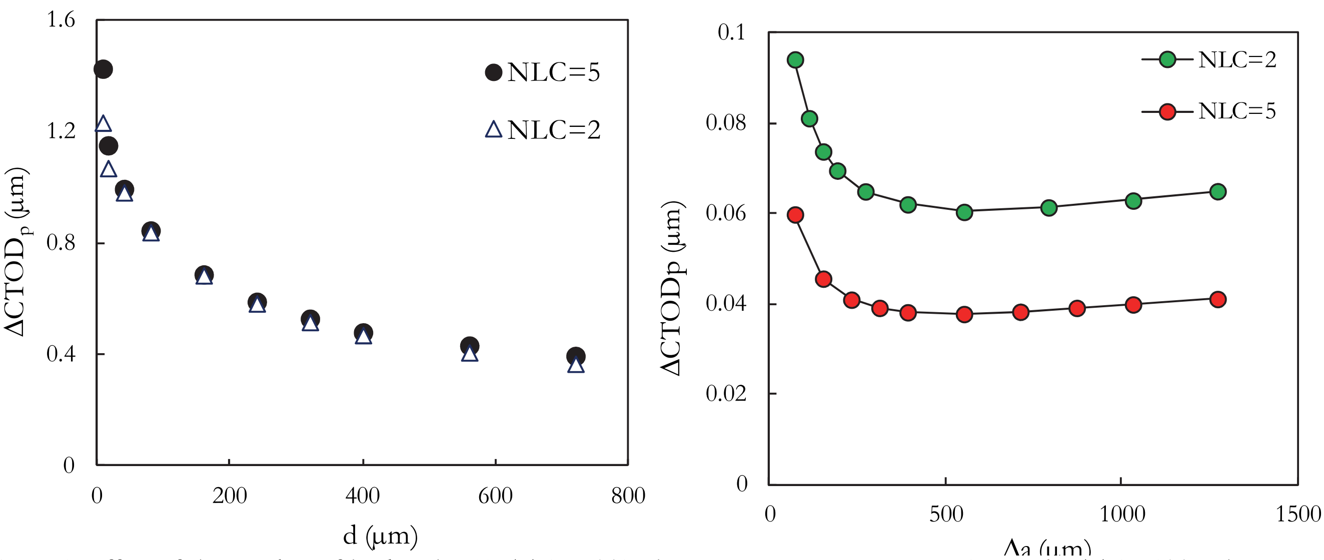


Figure 5: Effect of the number of load cycles (a) AA6082-T6; plane stress; F_{min}=0 N, F_{max}=360 N). (b) AA6016-T4; plane stress; F_{min}=0 N, F_{max}=140 N).

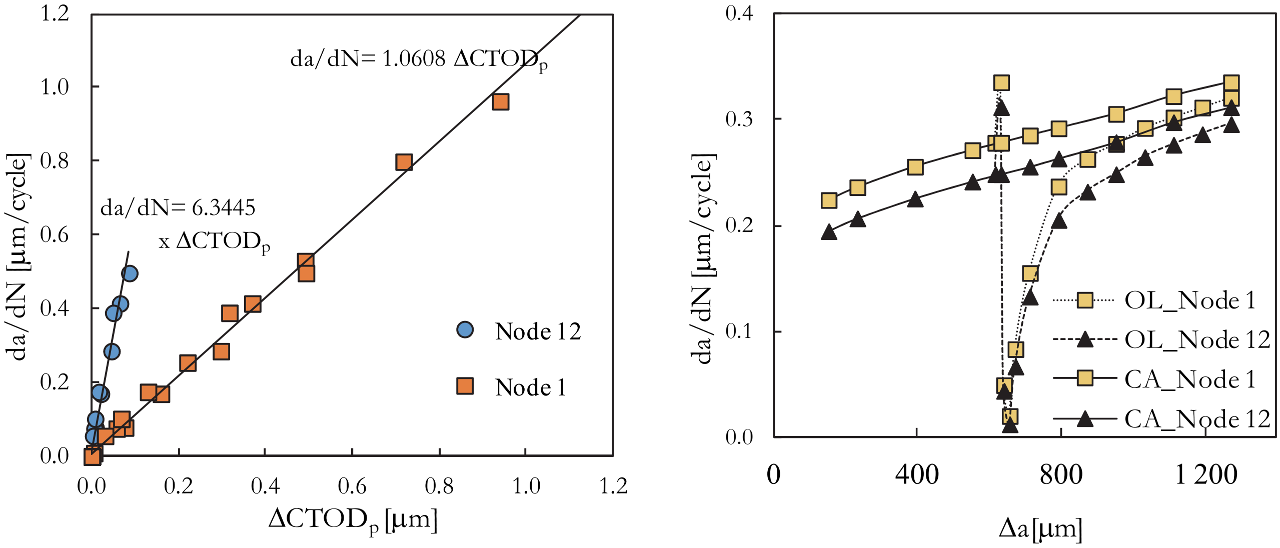


Figure 6: (a) Effect of the node on da/dN-$\Delta CTOD_p$ curves. (b) Prediction of the effect of an overload. (AA7050-T6; plane strain; NLC=2; F_{min}=209 N, F_{max}=419 N; F_{OL}=627 N).

CONCLUSIONS

The numerical predictions of $\Delta CTOD_p$ are quite sensitive to the position of the measurement point relatively to the crack tip. At relatively short distances, there is a fast decrease of $\Delta CTOD_p$ with departure from crack tip. At relatively large distances, there is a smooth but persistent decrease of predictions. Anyway, the measurement at quite remote positions is able to capture some plastic deformation, which is remarkable. Similar trends were obtained independently of load, material and stress state. The crack propagation, Δa, is also a major parameter. The first predictions, i.e. without significant propagation, are relatively high, which can be explained by the low hardening of the material, and by the relatively low values of crack closure. The propagation induces a relatively fast decrease of $\Delta CTOD_p$ which is linked to material hardening, followed by stabilization as the residual plastic wake is formed. After stabilization, there is a progressive increase of plastic CTOD with crack propagation, because there is a progressive increase of ΔK at the crack tip. A relatively low effect of finite mesh was found, which indicates that the predictions of $\Delta CTOD_p$ are robust relatively to this parameter. Anyway, the increase of mesh size increases the distance of the first node behind crack tip and therefore reduces the predictions based on this node. The number of load cycles between crack increments affects the values of $\Delta CTOD_p$. However, the level of influence considerably depends on the material properties. For the 6016-T4 aluminum alloy, a strong effect was observed; while for the AA6082-T6, the influence was limited. Further work is needed to understand the effect of material properties on crack tip plastic deformation, and on crack closure.

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REFERENCES

[1] Antunes, F.V., Sousa, T., Branco, R., Correia, L. Effect of crack closure on non-linear crack tip parameters, International Journal of Fatigue, 71 (2015) 53–63.

[2] Kawabata, T., Tagawa, T., Sakimoto, T., Kayamori, Y., Ohata, M., Yamashita, Y., Tamura, E., Yoshinari, H., Aihara, S., Minami, F., Mimura, H., Hagihara, Y. Proposal for a new CTOD calculation formula, Engineering Fracture Mechanics, 159 (2016) 16–34.
[3] Laird, C., Smith, G.C. Crack propagation in high stress fatigue, Philos. Mag., 8 (1962) 847–857.
[4] Pelloux, R.M. Crack Extension by alternating shear, Engineering Fracture Mechanics, 1 (1970) 170-174.
[5] Wu, J., Ellyin, F. A study of fatigue crack closure by elastic–plastic finite element for constant-amplitude loading. International Journal of Fracture, 82 (1996) 43–65.
[6] Antunes F.V., Branco R., Prates, P.A., Borrego, L., Fatigue crack growth modelling based on CTOD for the 7050-T6 alloy, Fatigue and Fracture of Engng Materials Structures, in press, DOI: 10.1111/ffe.12582
[7] Matos, P.F.P., Nowell, D., On the accurate assessment of crack opening and closing stresses in plasticity-induced fatigue crack closure problems, Eng. Fract. Mech., 74 (2007) 1579-1601.
[8] Borrego, L.P., Ferreira, J.M., Pinho da Cruz, A. J.D.M. Costa, Evaluation of overload effects on fatigue crack growth and closure, Eng. Fract. Mech., 70 (2003) 1379–1397.