SOME THOUGHTS ON FATIGUE CRACK GROWTH MODELS BASED ON ΔK_{EFF} *

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Abstract
After identifying fatigue crack closure under tensile loads, Elber postulated in the early 1970's that the fatigue crack growth behavior is controlled by the effective stress intensity (SIF) range $\Delta K_{eff} = K_{max} - K_{op}$, where $K_{op} > 0$ is the SIF that completely opens the crack. This assumption, which can explain many peculiarities of the fatigue crack growth (FCG) behavior under service loads, was readily accepted by the fatigue community and still is much used today to predict residual lives of cracked structures. However, Elber's closure cannot explain many other effects on FCG such as crack retardation or arrest after overloads under high $R = K_{min}/K_{max}$ when $K_{min} > K_{op}$; cracks that grow with constant rates under highly variable ΔK_{eff}; or cracks arrested at a given R that can resume to grow at a lower R without changing its ΔK_{eff}. Due to the major importance of this topic for practical applications, this work revisits the main arguments and evidence that support or else that question plasticity-induced crack closure as the primary cause for sequence effects in FCG, and raises some questions that should be properly discussed by all those who need to make residual life predictions.
Keywords: Opening loads; Fatigue crack growth behavior; Memory effects.

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1 INTRODUCTION

Fatigue crack growth (FCG) data collected since the 1960's show that variable amplitude loadings (VAL) can cause significant memory effects on FCG rates [1-2]. This means that the crack driving forces are history-dependent. Such load-order effects can have a major importance on fatigue life predictions, and simply cannot be neglected in most practical applications. As compared to the rates induced by identical driving forces that have not been previously affected by abrupt load changes, load order effects include delays, arrests, or even accelerations of FCG rates after tensile overloads (OL) or else after sudden decreases in the applied stress intensity factor (SIF) range ΔK and/or peak K_{max}; sudden fracture caused by very large OLs; and reduction of OL-induced delays after compressive underloads (UL), see Fig. 1 [3].

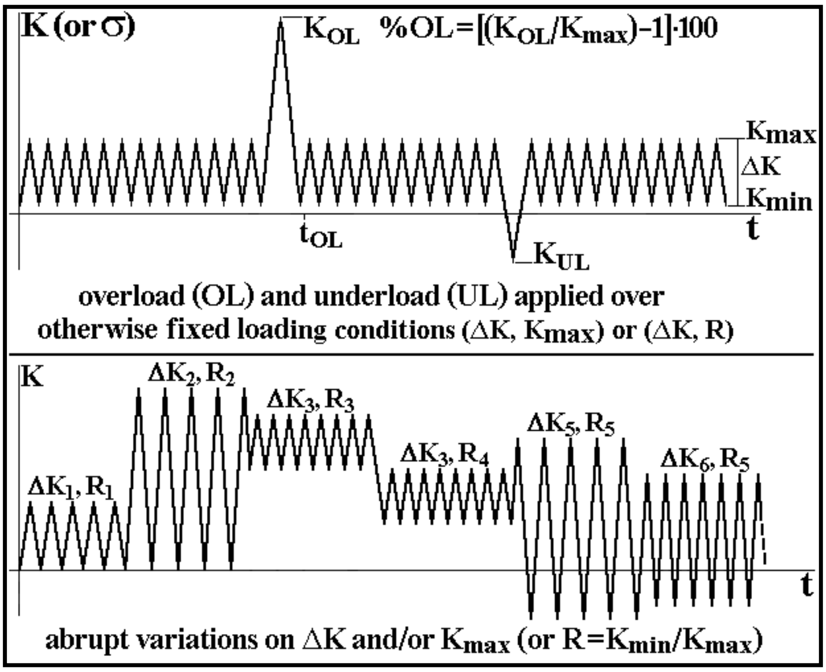

Fig. 1: Overloads, underloads, and abrupt load decreases can cause huge effects on FCG rates induced by VAL, much affecting subsequent fatigue cracking rates.

Load sequence effects on FCG can be induced by several mechanisms, which can be divided into three main classes [4]: (i) mechanisms that act along the crack faces, thus *before* the crack tip, such as fatigue crack closure induced by plasticity, roughness, phase transformation, and/or oxidation; (ii) mechanisms that act *at* the crack tip, like blunting, kinking, or bifurcation of the crack tip; and (iii) mechanisms that act *ahead* of the crack tip, like residual stresses and/or strains in the uncracked residual ligament *rl*. Such mechanisms are not exclusive, so they may act concomitantly. Moreover, their relative importance may depend on many factors, among them at least the load and the OL ranges and maxima; the number of OL cycles; the sizes of the crack and of *rl*; transversal constraints along the crack front; the previous residual stress state around the crack tip; the microstructure of the material; and the environment.

Skorupa [1,2] did an extensive review of the 20th century literature on load order effects on FCG, listing hundreds of papers with experimental and numerical evidence on such memory effects, and discussed qualitatively the mechanisms that may

induce them. She claimed that mechanisms related to plastic strains near the crack tip, such as plasticity-induced crack closure (PICC) [5-6] and residual stresses, can be used to qualitatively explain most memory effects on FCG data measured under VAL. She said as well that quantitative relations between crack closure measurements and FCG rates are not always satisfactory, but claimed that the reasons for some systematically found discrepancies remained unclear at that time.
In spite of many questions about the actual capability of PICC to quantitatively explain several memory effects in FCG under VAL [7-12], no other mechanism has received such acceptance by the fatigue community. Since Elber postulated that the actual FCG driving force should be the effective SIF range ($\Delta K_{eff} = K_{max} - K_{op}$, where K_{op} is the SIF that completely opens the fatigue crack), several semi-empirical models have been developed to estimate K_{op} and to predict FCG rates based on this idea. Indeed, classic software for residual life predictions under service loads based on Elber's ΔK_{eff}, such as NASGRO and AFGROW [13-14], are still extensively used by the aerospace industry nowadays.
Due to the major practical importance fatigue life predictions have in structural integrity assessments, the main objective of this work is to review some arguments and experimental evidence that support or rebut the idea that PICC would be the main cause for memory effects in FCG rates under VAL.

2 THE ΔK_{EFF} HYPOTHESIS

By making compliance measurements in a fatigue-cracked plate, Elber [5] identified crack closure by showing that a non-null SIF $K_{op} > 0$ was needed to completely open the crack. He imputed this crack closure phenomenon to tensile residual plastic strains that are always left on the wake of a growing fatigue crack, whose faces thus remained under compression when unloaded. Moreover, Elber *assumed* cracks cannot grow while their tips are not completely opened [6], such that the portion of their load cycle with $K < K_{op}$ would not induce any further fatigue damage. Hence, the actual FCG driving force would be ΔK_{eff} instead of the pair $\{\Delta K, R\}$. To justify this claim, Elber fitted FCG da/dN data measured under constant ΔK in 2024-T3 Al alloy specimens by Forman, Paris-Erdogan and by his $da/dN = C\Delta K_{eff}^m$ rule, obtaining *rms* errors of 28, 27 and 21 respectively. This apparently better performance of his model was hence used to sustain his hypothesis that ΔK_{eff} would be the actual FCG driving force, even though such a data fitting cannot be considered a proof, especially with so similar errors.
Anyway, fatigue crack closure can be easily measured and it can at least qualitatively explain many memory effects under VAL. Moreover, the key point behind the *ΔK_{eff} hypothesis* is that the *rl* ahead of the crack tip cannot suffer any further fatigue damage below K_{op}, either during the loading or the unloading part of the load cycle, because fatigue crack closure would completely shield the crack tip. Figure 2 schematizes the behavior of a point in the *rl* ahead of the crack tip under a $P_{min} \rightarrow P_{max} \rightarrow P_{min} > 0$ load cycle. An initially linear elastic behavior A→B is expected during the loading stretch, followed by plasticity up to point C, see Fig. 2a. The unloading stretch is elastic until the stresses inside the monotonic plastic zone *pz* ahead of the crack tip reach the yield strength of the material under compression at point D, initiating the formation of the reverse plastic zone pz_r until the final unloading point E.
If crack closure can indeed totally shield the crack tip, as proposed by Eber, during the loading stretch it cannot allow any deformation ahead of the crack tip until the

load reaches the opening load P_{op}, see Fig. 2b. The inverse should occur during unloading, so the deformation should stop after the crack closure point (for simplicity considered as equal to the opening point in the figure). However, if a strain measurement ahead of the crack tip during a load cycle is like Fig. 2a, crack closure does not totally shield the crack as proposed by Elber, since this load cycle portion would contribute to fatigue damage, mainly during unloading when the reverse plastic zone is forming.

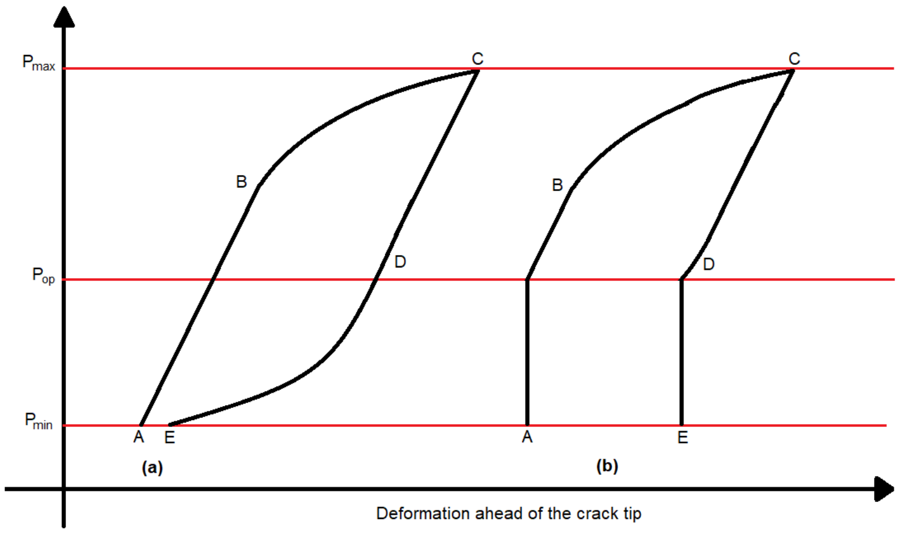

Figure 2. Schematic behavior ahead of the crack tip: (a) no shield, (b) crack tip completely shielded.

In view of that, Elber's own results, depicted in Fig. 3 [6], can be used to question his ΔK_{eff} hypothesis. Figure 3 shows the applied stress versus the displacement measured by a clip gage mounted ahead of the crack tip before, during, and after an OL. The circles represent the crack opening point. It is clear that the material ahead of the crack tip displaces under the opening load both during the loading and the unloading portion of the load cycle.

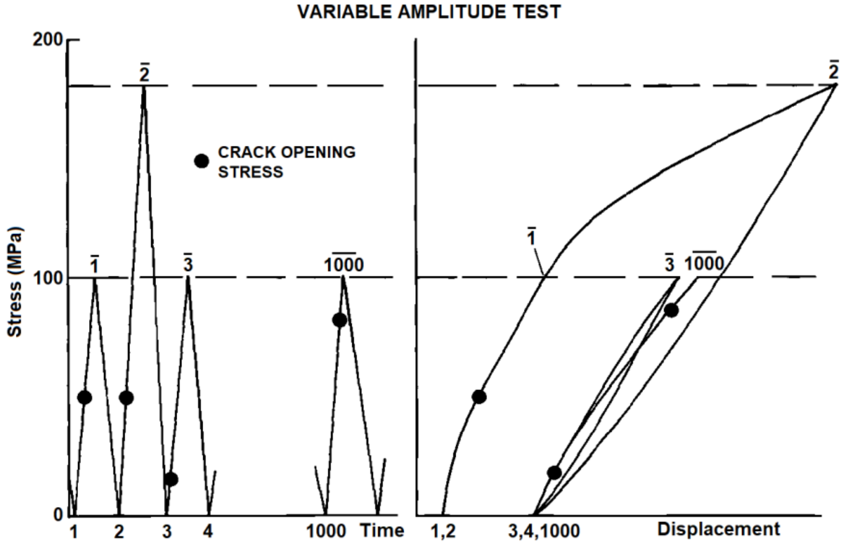

Figure 3. Crack opening stress and displacements ahead of the crack tip [6].

3 CORRELATION BETWEEN ΔK_{EFF} AND FATIGUE CRACK GROWTH RATES

Countless authors tested Elber's hypothesis, but most just to reaffirm his idea, instead of to understand the real influence of PICC on FCG. von Euw et al. [15] e.g.

tested 2024-T3 Al 3.2mm thick specimens to analyze OL effects on FCG rates. They used Elber's $da/dN = C[(0,5 + 0,4R)\Delta K]^n$ empirical equation to estimate ΔK_{eff} [6], and then concluded that ΔK_{eff} was the driving force for FCG due to its reasonable correlation with their da/dN data. However, this evidence is certainly questionable when actual K_{op} values are not measured, since data-fitting cannot constitute a scientific proof.

Minimum FCG rates after the OL were observed after crack increments $pz/8 < \Delta a < pz/4$, an evidence of delayed FCG retardation, according to the authors. In fact, K_{op} should reduce just after the OL since it tends to blunt the crack tip, locally increasing ΔK_{eff} and accelerating the subsequent FCG rates [9,16], not immediately lowering them as shown in the paper. However, since K_{op} levels were not measured, this cannot be considered an evidence against crack closure.

Hertzberg et al. [17] tested 7mm thick Al-Cu-0.7Si Al alloy and 9mm thick 4340 steel specimens, and studied the effect of increasing K_{op} by using 50, 75, and 100μm thick shims between the crack faces. For the Al alloy, K_{op} increased from 13% to 30%, 50%, and 93% of K_{max}, while FCG rates reduced by a factor of 1.2, 2.7, and 4.7. However, if really caused by ΔK_{eff}, according to Elber's estimates, FCG rates should reduce by a factor of 16, 27, and 800 respectively. Similar results were found for the tested 4340 steel. So, FCG rate estimates based on measured K_{op} lead to *unconservative* predictions. This experimental evidence indicates that there is fatigue damage below K_{op}, contrary to Elber's hypothesis. However, Hertzberg et al. did not question Elber's idea, and simply assigned this difference to a possible error induced by the crack closure measurement method – an extensometer at the crack mouth. Far field crack closure measurements are sometimes questioned in the literature because they could yield lower values than near field measurements [18-19], but many authors do not report any significant K_{op} differences when measuring it by both techniques [7-8, 16]. So, the error could still be higher with a near field measurement.

Hertzberg et al. [17] also measured FCG rates and K_{op} levels after a compressive UL followed by fixed $\{\Delta K, R\}$ cycles (Fig. 4). The FCG rate stabilized after a crack increment $\Delta a \cong 2\text{-}3mm$ from the UL point, while K_{op} only stabilized after $\Delta a \cong 9\text{-}10mm$. So, after a growth $\Delta a \cong 3mm$, the FCG rate remained essentially constant under *variable* ΔK_{eff}. This evidence against Elber's hypothesis was not explained by the authors.

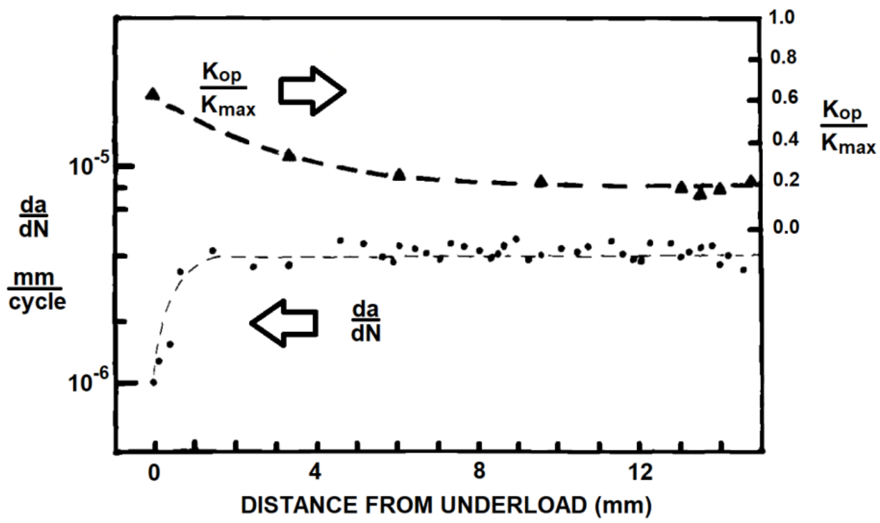

Figure 4. FCG rate and K_{op} for an Al alloy after a compressive underload [17].

Fleck [16] measured FCG rates and K_{op} levels before and after an OL in BS4360 50B 3 and 24mm thick low strength steel specimens, to grow cracks under plane stress and plane strain conditions under otherwise constant ΔK. Extensometers at the crack mouth and strain gages at the specimen back face and at the crack surface 2.5mm behind the crack tip were used to measure K_{op}. Figure 5 presents the measured FCG rates (Fig. 5a) and opening loads (Fig. 5b), which are indirectly represented by the closure ratio $U = (K_{max} - K_{op})/(K_{max} - K_{min})$. In the 24mm thick specimen, even though the FCG rates were equal at the center and at the surface of the specimen, the opening load at the surface was higher. But if ΔK_{eff} is the driving force for FCG, why would the rates be the same at the center and at the surface for different K_{op} amplitudes? Just after the OL (crack increment $\Delta a = 0$), the opening SIF K_{op} at the surface reduced to values near K_{min} ($U \approx 1$), but without a proportional increase in FCG rates. For this thick specimen, K_{op} gradually reduced for crack increments between $\Delta a = 2$ to $8mm$, but the corresponding FCG rate kept fairly constant under a variable ΔK_{eff}.

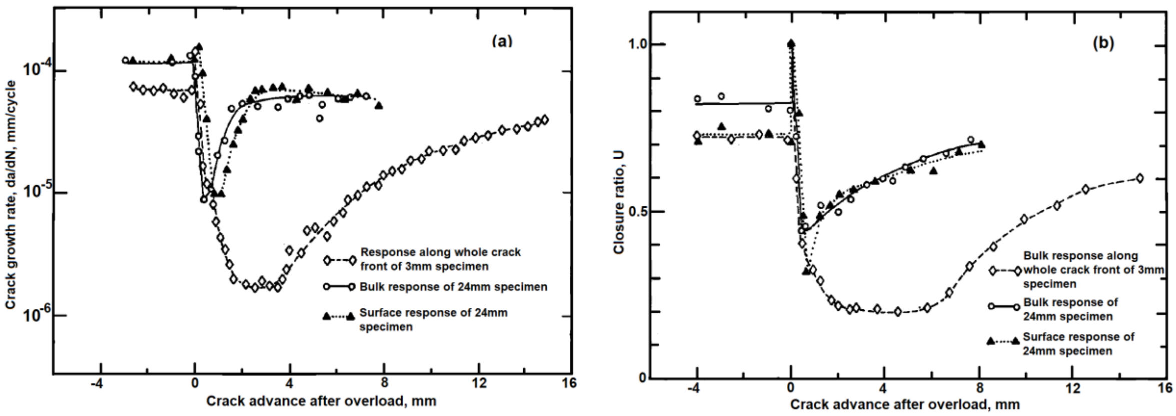

Figure 5. FCG rate (a) and crack closure (b) measurements [14].

For the thin 3mm specimens, K_{op} remained constant between $\Delta a = 2$ and $6mm$, but the FCG rate started to increase just before Δa = 4mm. Assuming these measurements are coherent, and recalling that the author measured the opening load using three different methods, these experimental results indicate that ΔK_{eff} was not the controlling FCG parameter. However, the author assigns the K_{op} inability to explain the FCG behavior to a "discontinuous closure" behavior. According to him, a residual hump of stretched material would be created by the OL, which would become the point of first contact between the crack surfaces along the subsequent FCG. This material would act like a spring, allowing cyclic displacements ahead of the crack tip below K_{op}. So, the SIF range that actually loads the crack tip would be higher than indicated by the K_{op} measurements and, consequently, FCG rates would be higher than predicted by ΔK_{eff}. Even though it would be simpler to recognize that ΔK_{eff} was not controlling the FCG behavior in this case, the author preferred to create an elaborate argument to explain the contradictions between the measured K_{op} and FCG rates.

Castro et al. [7] measured K_{op} (using redundant near and far field compliance methods and digital image correlation (DIC) techniques, which yielded near identical K_{op} data) and FCG rates in 2mm and 30mm thick specimens of SAE 1020 steel under constant ΔK and K_{max} (and thus R), see Fig. 6, to propagate the cracks under plane stress and plane strain conditions. Notice that although the opening loads K_{op}

continuously reduced as the cracks advanced (increasing the corresponding ΔK_{eff}), the FCG rate kept constant in all tests. Therefore, the FCG behavior was not controlled either by ΔK_{eff} in these easily reproducible tests.

Testing C(T) specimens of A542/2 steel under plane strain conditions under otherwise constant $\Delta K = 10MPa\sqrt{m}$ and $R = 0.7$, Castro et al. [4] observed FCG retardation after an OL ($K_{OL} = 1.5 \cdot K_{max}$), see Fig. 7a. However, due to the high R used in these tests, the crack remained fully open before and after the OL, i.e. $K_{min} > K_{op}$, as the linear compliance measurements prove in Fig. 7b. Since $\Delta K_{eff} = \Delta K$ before and after the OL in these tests, the memory effects cannot be explained by Elber's PICC, simply because there is no crack closure either before or after the OL.

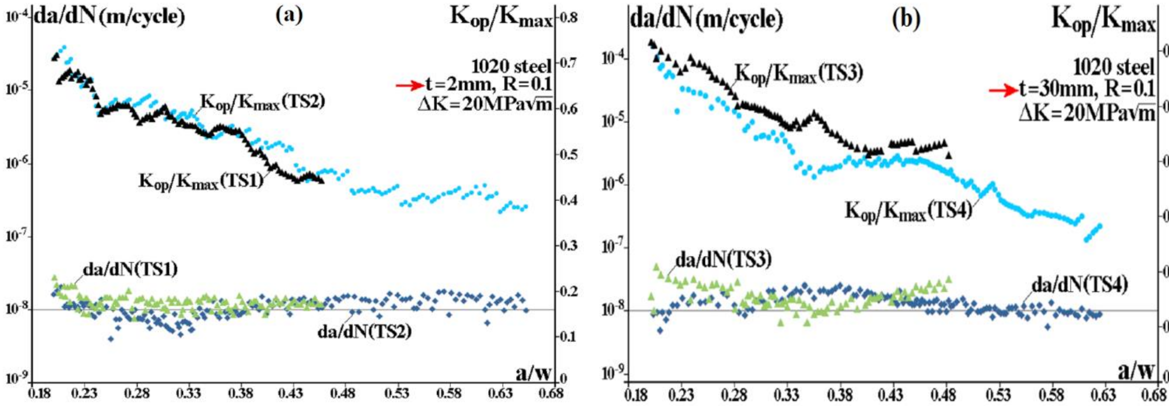

Figure 6. FCG rate and opening loads for specimens of 2mm (a) and 30mm (b) [5].

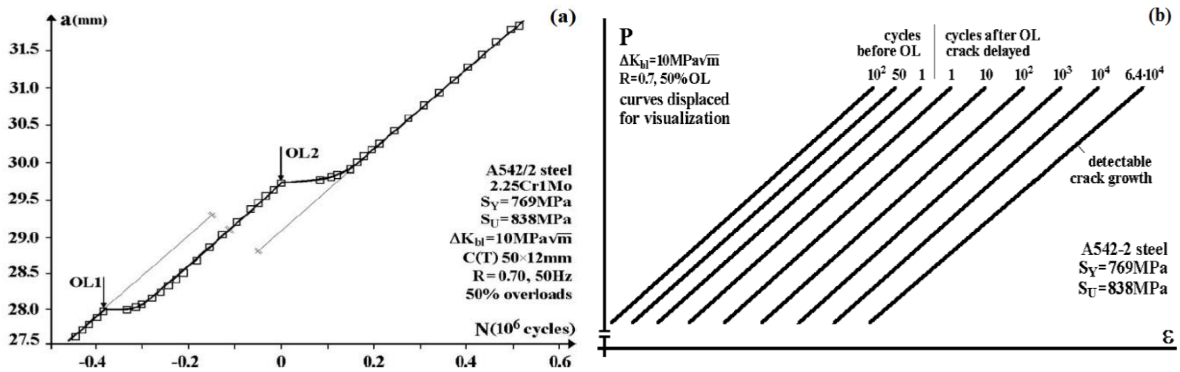

Figure 7. FCG rate (a) and opening loads (b) results from [6].

Davidson et al. [9] performed OL-induced FCG retardation tests in 7091-T7E69 Al. Figure 8a shows their FCG rates and ΔK_{eff} (measured by SEM techniques) vs. crack increment Δa (positive after the OL), measured before and after an OL ($\Delta K_{OL}/\Delta K = 2.85$). Figure 8b shows similar results for an OL followed by an UL. Notice in Fig. 8a that even with the increase in ΔK_{eff} observed just after the OL, the corresponding FCG rates reduced immediately. According to the authors, the residual displacements ahead of the crack tip after an OL is normally tensile and the crack faces remain opened by a distance of several millimeters behind its tip. These measurements confirm the cause for the opening load reduction after an overload event. On the other hand, when the OL is followed by an UL, as shown in Fig. 8b, the FCG rate increased about 8 times just after the OL. To correlate this FCG rate increase with ΔK_{eff}, the exponent m of the rule $da/dN = C\Delta K_{eff}^{m}$ should be 5.83. The authors do not report their m value, but using a median estimate considering 54 series 7xxx Al alloys, the m value would be 3.2 [20]. Figure 8b also shows a continuous decrease in subsequent ΔK_{eff} values, but with an increase of FCG rates for Δa > *0.1mm* crack increments. These data clearly contradict Elber's hypothesis. A compressive UL increases the reversibility of the displacements during unloading and decreases the residual displacements ahead of the crack tip with a respective increase of the plastic compressive deformation [9].

Toyosada and Niwa [10] considered that fatigue cracks cannot grow while new plastic strains are not induced ahead of their tips. They developed a way to measure the load that tends to initiate the formation of new tensile plastic strains during FCG tests in SM-41B steel 10mm thick specimens. The authors showed that the threshold SIF is related to the point in which no new plastic strains are formed at the crack tip, where there is no more damage. They verified as well that FCG rates did not correlate well with the measured ΔK_{eff} for the entire tested range. This way, they identified that ΔK_{eff} was not the driving force for FCG in their tests. The results presented in [10] also indicate the threshold SIF would not be an evidence of the influence of K_{op} in FCG, as claimed by some researchers.

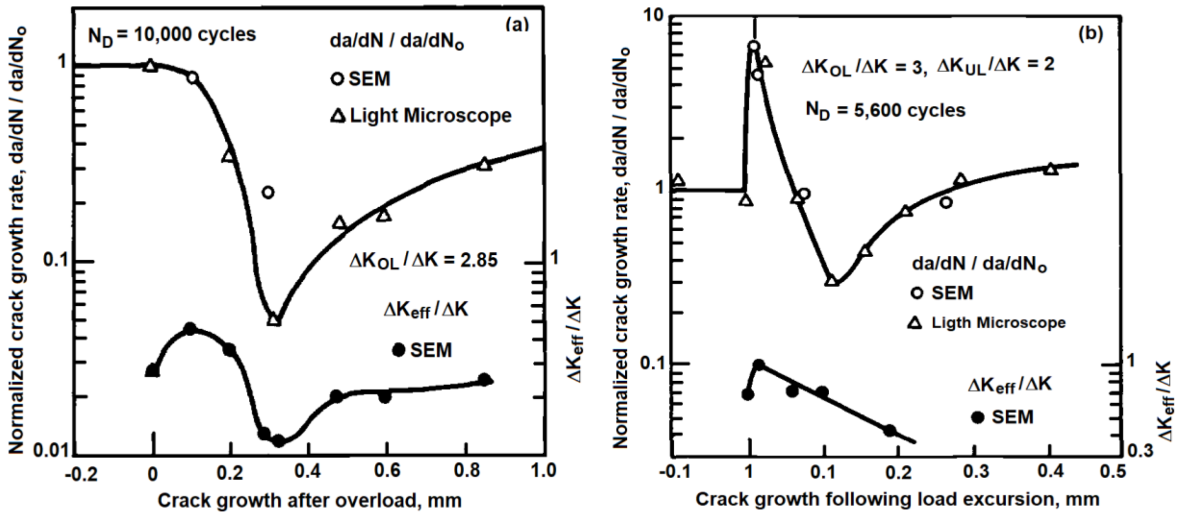

Figure 8. FCG rate and ΔK_{eff}: (a) $\Delta K_{SC}/\Delta K$ = 2.85, (b) $\Delta K_{SC}/\Delta K$ = 3 followed by $\Delta K_{SubC}/\Delta K$ = 2 [9].

Similar tests were conducted by Lang [11], who measured the minimal SIF needed to propagate fatigue cracks. Lang claims that this would occur when the material adjacent to the crack tip becomes free of compressive residual stresses. He verified that this SIF increases after OLs, and decreases with the reduction of the minimum load during unloading. In FCG tests where an OL is followed by a compressive UL, this SIF reduces with the increase of the modulus of the compressive underload. The SIFs measured by Lang are in accordance with the displacement measurements presented in [9]. These results indicate that FCG is directly related to the interaction between the monotonic and the reverse plastic zones. Since higher compressive residual stresses must be relieved to propagate a crack inside a monotonic plastic zone hypertrophied by an OL, OLs tend to reduce FCG rates and to increase the SIF needed to propagate the crack. On the other hand, ULs after an OL tend to increase the reverse plastic zones, increasing FCG rates and decreasing the SIFs needed to grow the crack. These hypotheses are coherent with the results presented in [8-11].

Results from Chen et al. [12] are particularly interesting. They studied the ΔK_{eff} concept through FCG tests of Al specimens keeping R = 0.3 fixed and gradually reducing ΔK until reaching the threshold ΔK_{th} (defined as da/dN < 10^{-12} m/cycle). At the threshold, the load cycle was K_{max} = 3MPa√m, K_{min} = 0.9MPa√m and the

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measured opening load was K_{op} = 2MPa√m. After reaching ΔK_{th}, K_{min} was reduced to zero to continue the tests under R = 0 without changing ΔK_{eff}, but causing a significant increase in the FCG rate, as shown in Fig. 9a. Compliance measurements along the test confirmed that K_{op} and thus ΔK_{eff} did not change during the tests, see Fig. 9b. These results indicate that the load cycle portion below the opening load contributed to the FCG process, a strong evidence against the "ΔK_{eff} is the FCG driving force" *hypothesis*. Indeed, the reduction in K_{min} increased ΔK and the FCG rates, but not ΔK_{eff}, which remained constant. An arrested crack that resumes growing after an R reduction that did not alter ΔK_{eff} is an undisputable evidence of fatigue damage induced below K_{op}. This damage can be related to the increase of the reverse plastic zone size during the unloading cycle part, which increases the plastic strain range.

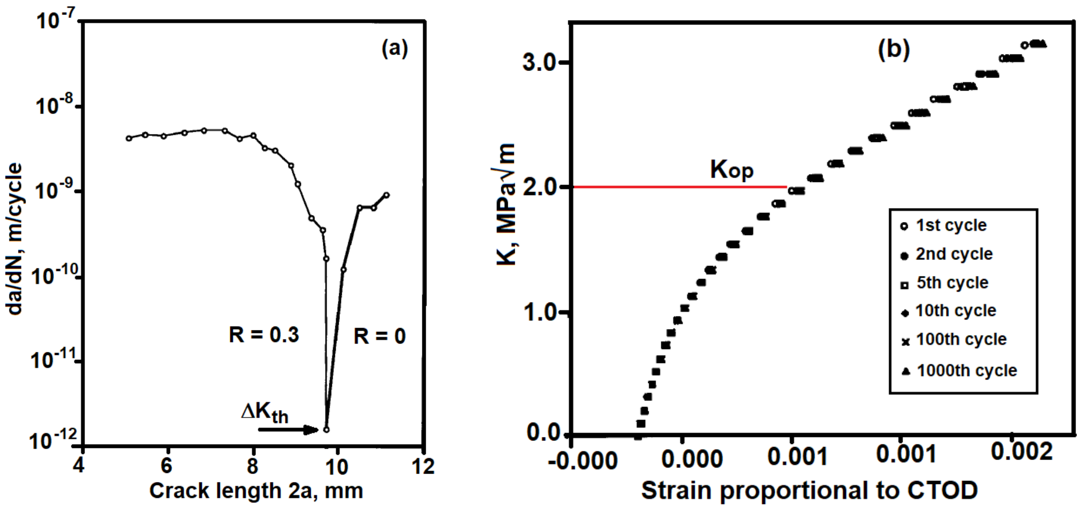

Figure 9. FCG rate (a) and opening load (b) for a 2024 Al alloy [10].

Another evidence presented by Vasudevan et al. [22] can be used to seriously question the actual ΔK_{eff} role in FCG: the threshold for various alloys tested in high vacuum is R-independent, see Fig. 10. This data was measured by various authors, and includes Al and Ti alloys, steels, Ni superalloys, and even single crystals, and it clearly indicates that PICC is either negligible or non-existent in vacuum. Since vacuum suppresses the effects of the environment, but not of plasticity, how could the measured ΔK_{th} values remain constant over the entire R range, if they were caused by PICC? Vasudevan claims that this set of data indicates that the FCG threshold behavior normally explained in terms of crack closure effects should be, in fact, related to the environment contribution to the FCG process.

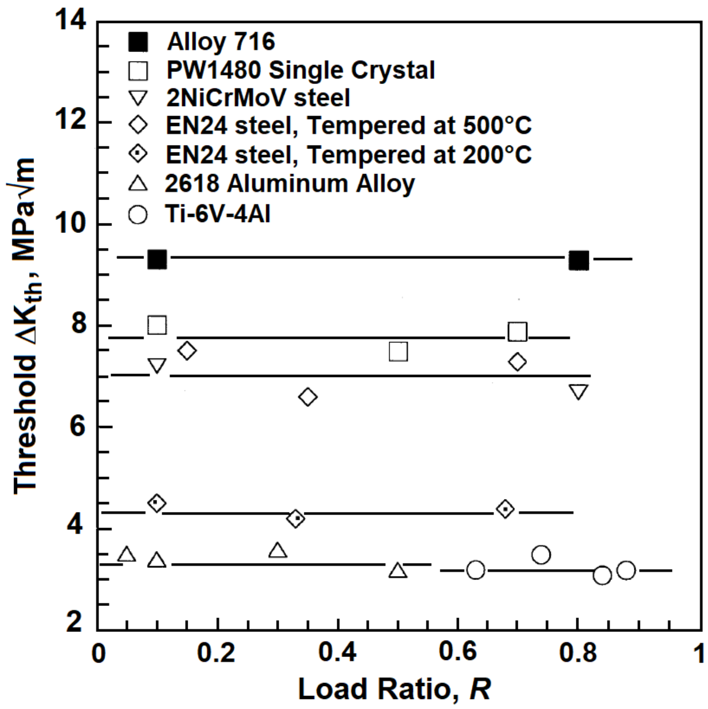

Figure 10. Threshold measurements in vacuum [20].

The ΔK_{eff} hypothesis proposed by Elber [6] assumes the crack tip is completely shielded from any fatigue damage below K_{op}. However, due to the material elastic-plastic behavior, even with the crack completely closed under tensile loads, shielding would only affect the crack geometry, since its faces indeed do not displace after closed. But the gradual closing of the crack faces would not necessarily avoid at all increments of the plastic strain range during unloading below K_{op} [21]. That would be the physical reason why ΔK_{eff} can overestimate the PICC effect and generate non-conservative FCG predictions. This can possibly be the cause for the many inconsistencies observed when trying to use crack opening loads to explain some characteristics of the FCG behavior. This point is further explored next.

4 THE FATIGUE CRACK DRIVING FORCE

Many experimental pieces of evidence based on direct K_{op} measurements were presented and discussed above to question the actual role of ΔK_{eff} in FCG. They indicate that what happens in the uncracked ligament ahead of the crack tip is more important than what happens in the plastic wake that encloses the crack faces behind the crack tip. In fact, such K_{op} data indicate that the crack closure phenomenon seems to be a consequence of the FCG behavior, rather than its cause. Even many authors that support the idea that ΔK_{eff} is the driving force for FCG present results that put in check this idea.

It is well known that fatigue cracks do not grow through virgin material. Instead, they grow by cutting material that has already been damaged by the monotonic *pz* and by the reverse or cyclic pz_r plastic zones that always form ahead of their tips. Load peaks K_{max} control the size as well as the magnitude and the distribution of the tensile plastic strains inside *pz*, so of the consequent residual stresses caused by them. Load ranges ΔK do the same within pz_r, in which the residual strains are compressive rather than tensile. Load peaks K_{max} activate monotonic damage mechanisms that depend on it, like environmentally assisted cracking and fracture, whereas load ranges ΔK drive cyclic damage mechanisms, which are also affected by the peak loads K_{max} and by the total residual stresses left ahead of the crack tip. The total fatigue damage in each load cycle depends on both its range and peak ΔK and K_{max}, and on the residual stress field ahead of the crack tip induced by the previous loading history. In other words, memory effects observed in FCG result from a competition of two physical phenomena: damage accumulated by cyclic plastic strains, and residual stresses ahead of the crack tip [23]. Monotonic plastic zones may cause compressive residual stresses that shield the crack tip during FCG. Reverse plastic zones cause direct fatigue damage.

Closure loads may influence the FCG behavior as long as they can affect the stress/strain or the elastoplastic hysteresis loops ahead of the crack tip. FCG models cannot assume the material ahead of the crack tip is completely shielded while the tip is not totally open. Hence, residual life predictions made by ΔK_{eff}-based FCG models should be supported by proper EP loops measurements ahead of the crack tip, or at least by decent K_{op} data.

OLs increase both pz and pz_r, as well as the mainly compressive residual stress field and the accumulated fatigue damage ahead of the crack tip. They may also affect the crack tip geometry, inducing branching that may further reduce FCG by decreasing its local SIFs just after the OLs [24]. Competition between these effects determines the subsequent FCG rates. Initial accelerations observed after some OLs is related to the increase in the damage accumulated by plastic strains, whereas the shielding effect of compressive residual stress fields reduces pz_r and retards FCG rates. So, if memory effects on FCG are mainly due to plasticity, then both the pz and pz_r sizes, as well as the consequent FCG rates, should not be affected anymore by them after the crack crosses the plastic zones hypertrophied by the OL. This competition can qualitatively explain most memory effects in FCG induced by VAL.

An experimental piece of evidence of the compressive residual stress field after an OL was obtained by Withers et al. [25]. They used x-ray diffraction (XRD) and digital image correlation (DIC) to calculate the stress field ahead of the crack tip before and after the overload in a C(T) specimen of a bainitic HY80 steel. Figure 11a shows the stresses at the maximum load and Fig. 11b the stresses at the minimum load. The effect of the residual stress field generated by the OL is to reduce the amplitude of the stress at the maximum load (compare in Fig. 11a the stresses at OL-1 and at OL+40) and by almost the same ratio to reduce the residual stress field at the minimum load (see in Fig. 11b the stress at OL-1 and at OL+40). These stress fields after the OL confirm the shielding effect of the compressive residual stress. Lower monotonic and reverse plastic zones, while the crack is inside the plastic zone induced by the previous OL, reduce the cyclic plastic strains and cause retardation in the subsequent FCG rates.

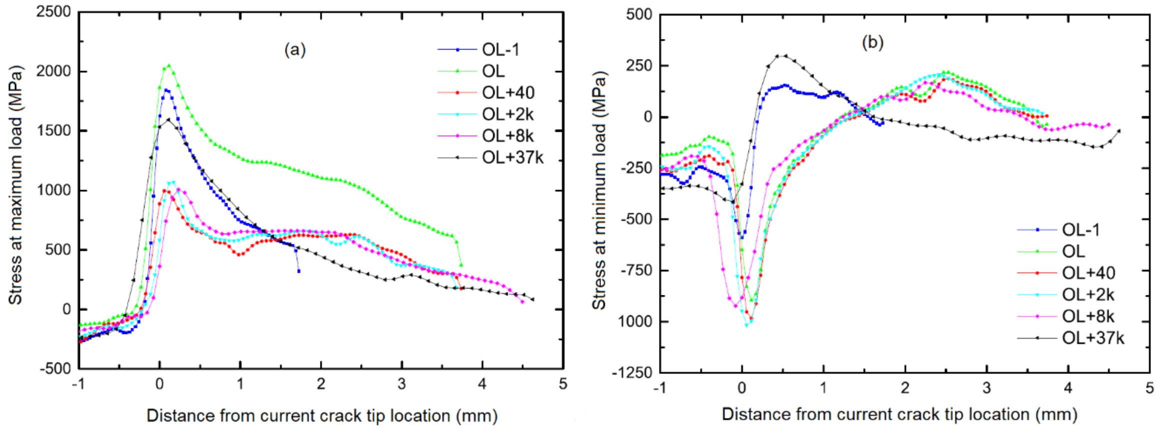

Figure 11. Stress profile at the maximum load (a) an at the minimum load (b) [25].

5 CONCLUSION

This humble review of the literature shows that the crack closure concept cannot be dogmatically accepted. There are plenty of experimental data to seriously question the actual role of ΔK_{eff} in FCG. In particular, experimental evidence indicates that there is damage below the crack opening load, a fact that invalidates the ΔK_{eff} hypothesis. An alternative and probably sounder way to explain memory effects in FCG rates can be based on two competitive mechanisms: cumulative damage due to cyclic strains, and residual stresses ahead of the crack tip, which can be associated with the sizes of the monotonic and reverse plastic zones that always follow fatigue crack tips. An important practical consequence of this fact is that residual fatigue life predictions based on ΔK_{eff} hypothesis should not be taken for granted by structural engineers.

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