A. Cernescu, Frattura ed Integrità Strutturale, 41 (2017) 307-313; DOI: 10.3221/IGF-ESIS.41.41

Focused on Crack Tip Fields

The influence of crack tip shielding on fatigue crack propagation

Anghel Cernescu
Politehnica University of Timisoara, Romania
anghelcernescu@gmail.com, anghelcernescu@yahoo.com, http://orcid.org/0000-0001-9513-9643

ABSTRACT. The fatigue crack propagation is one of the major problems and of the real concern in the evaluation of the structural integrity of components. This is due to the fact that once a fatigue crack has been detected it is also known its effect on the component; respectively it will cause failure at one time. In this situation, the problem is focused on determining the character of propagation of the crack so that it can be estimated and respectively delayed as possible the failure moment. The fatigue crack propagation character is determined by the stress state at the crack tip and the behavior of the material in which the crack is propagates. One of the phenomena with great influence on the fatigue crack propagation character is the crack tip stress shielding phenomena. In this paper the overloading effect is explained in terms of crack tip shielding mechanisms that guide the fatigue crack growth in plastic zone. The results indicate a change of fatigue crack propagation character once its tip enters into a plastic zone.

KEYWORDS. Fatigue crack growth rate; Crack tip shielding; Crack closure; Overloading cycle; Plastic zone.

Citation: Cernescu, A., The influence of crack tip shielding on fatigue crack propagation, Frattura ed Integrità Strutturale, 41 (2017) 307-313.

Received: 28.02.2017
Accepted: 03.05.2017
Published: 01.07.2017

INTRODUCTION

One of the current approaches of fatigue damage predictions is based on the damage tolerance concept. This concept starts from the premise that each component has a potential defect and the fatigue life is based on the number of cycles required for an initial crack to grow to the critical value. Using an appropriate fatigue crack growth equation, the initial fatigue crack is propagated through iterative calculations that take into account the loading spectrum, material properties and component geometry. One of the elements that confer the degree of accuracy of fatigue crack growth predictions is represented by the crack closure phenomenon. According to the review made by M. N. James, [1], on the crack closure, the first study that has highlighted such a phenomenon was presented by Christensen in 1963, [2]. Performing fatigue crack growth tests on center-cracked specimens of 2024-T3 aluminum alloy it was observed an increase in fatigue life occurred in the presence of trapped oxide particles between the fracture surfaces.
However, of reference are the Elber's studies from 1970 and 1971, [3-4]. Based on residual stress distribution and resultant forces analysis in center-cracked plate specimen under zero-to-tension loading, Elber showed that the crack is fully open only for a part of the loading cycle. This being attributed to the field of plastic deformations in the wake of

crack tip. Due to direct implications in fatigue crack growth retardation, the crack closure phenomenon has been extensively analyzed both experimentally and numerically.

In 1988, R.O. Ritchie, [5], brings into discussion the idea that fatigue crack growth retardation can be achieved by reducing the applied load or by toughening the material. He presents two classes of toughening mechanisms: intrinsic, by increasing the inherent microstructural resistance to crack advance and extrinsic, where the toughness arises from mechanisms of *crack tip shielding*. This term was first introduced and covers four categories: crack deflection and meandering, zone shielding (transformation toughening, microcrack toughening, crack wake plasticity, crack field void formation, residual stress fields, crack tip dislocation shielding), contact shielding (wedging, bridging, sliding, wedging + bridging), combined zone and contact shielding (plasticity-induced crack closure, phase transformation-induced closure).

In the same manner Pippan and Hohenwarter, [6], describes the role of intrinsic and respectively extrinsic mechanisms in fatigue crack propagation, where the intrinsic mechanisms are responsible for the formation of new fracture surfaces at the crack tip by cyclic deformation. In a different study, Mutoh et al., [7], show that in steels with ferritic-pearlitic microstructure (networked or distributed pearlite), besides the crack closure phenomenon there are also other mechanisms of crack-tip stress-shielding phenomena, respectively branching and interlocking. They define an effective crack tip stress intensity factor range, $\Delta K_{eff,tip}$, that manages to better correlation of fatigue crack propagation data in a single curve, compared to the well-known ΔK_{eff}. In Reference [8] it is described a model of fatigue crack propagation based on dislocation emission at the crack tip and respectively the dislocations in the plastic zone and plastic wake. The fatigue crack growth rate into a plastic zone can be reduced through a dislocation crack tip shielding mechanism. However, this mechanism can stop the advancing of the crack when the crack tip is fully shielded, but does not guarantee that do not form another tip that lead to an extension of the crack in another direction.

Given the above, one can say that fatigue crack propagation is guided by the crack tip shielding mechanisms that acts actively by forming new crack tips and respectively passive crack tip shielding mechanisms. The passive crack tip shielding mechanisms cannot create crack tips if the applied loading does not exceed a certain value. From this point of view plasticity-induced closure, as extrinsic mechanism of combined zone and contact shielding, can be considered passive. If the applied loading does not exceed P_{op}, the crack tip remains protected by the plastic field and the crack does not extend.

In the following sections it is presented an analysis of fatigue crack growth into a plastic deformation zone given by an overloading cycle. In the case of constant amplitude loading the introduction of an overloading cycle leads to increasing of the crack opening load corresponding to that cycle. If the crack opening force associated to the overloading cycle, $P_{op,OL}$ is greater than the maximum force of the constant amplitude loading, then the crack tip is shielded, fig. 1.

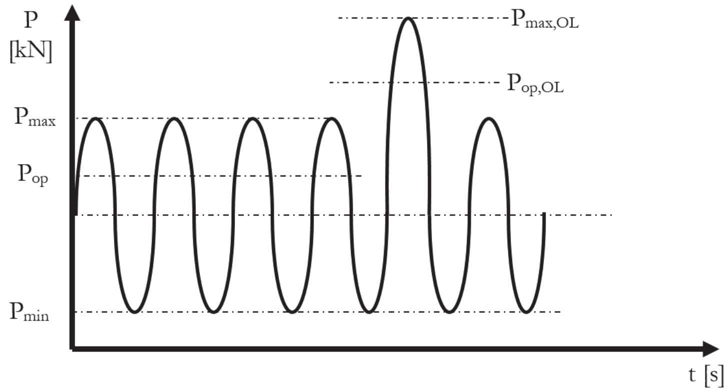


Figure 1: The constant amplitude loading with an overloading cycle.

However, it is known that the fatigue crack propagates within the plastic zone created by the overloading which indicates that once the material is strengthening there are active crack tip shielding mechanisms that helps the crack to growth through the retardation period.

MATERIALS AND METHODS

For this analysis, fatigue crack growth rate tests were carried out in elastic-plastic steel. The chemical composition and mechanical properties of the material are given in Tabs. 1 and 2. The fatigue crack growth rate tests were conducted on CT samples, according to ASTM E 647, [9]. Also, tests have been performed corresponding to plane strain and respectively plane stress state.

C	Si	Mn	P	S	Cr	Ni	W	Al	Cu	N
0.15	0.22	1.46	0.04	0.02	0.05	0.03	0.03	0.04	0.02	0.01

Table 1: The chemical composition of steel, [%].

Material	Young's modulus [MPa]	Yield strength [MPa]	Ultimate strength [MPa]	Elongation [%]
Low-alloy steel	205000	255	368	30

Table 2: The mechanical properties of tested material.

Fatigue crack growth rate in plane strain state

Two CT samples were tested for plane strain conditions with dimensions shown in Fig. 2 and a thickness of 10 mm. One sample was tested at constant amplitude loading with stress ratio 0.1 and maximum load of 8 kN.

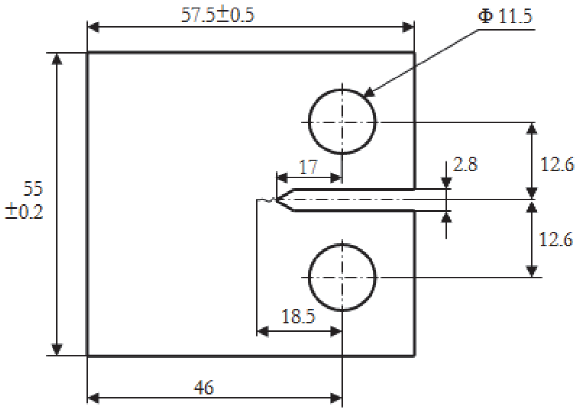


Figure 2: The dimensions of CT samples used in fatigue crack growth rate tests, (units: mm).

At the second sample, after fatigue pre-cracking it was introduced an overloading cycle with maximum load of about 20 kN and then continued testing at constant amplitude loading with maximum load of 8 kN and stress ratio 0.1.

Fatigue crack growth rate in plane stress state

For plane stress state were used two CT samples with the same dimensions as in Fig. 2 but thickness of 2.4 mm. In all cases the sample dimensions respect the conditions required by ASTM E 647. After fatigue pre-cracking both samples were tested at constant amplitude loading with maximum load of 2 kN and stress ratio 0.1. Also, to both samples were applied an overloading cycle with maximum force higher with 26 % of the maximum force of constant amplitude loading and respectively 82 %.

During the entire fatigue crack propagation tests have been recorded the applied force and respectively the crack opening displacement (COD) corresponding to each loading cycle. Also, the compliance technique was used to determine the crack length.

RESULTS AND DISCUSSIONS

All samples were examined by scanning electron microscopy (SEM) aiming to crack evolution before and after the overloading cycle. For plane strain state it was determined the variation of fatigue crack growth rate function of stress intensity factor range for constant amplitude loading with stress ratio 0.1, fig. 3.

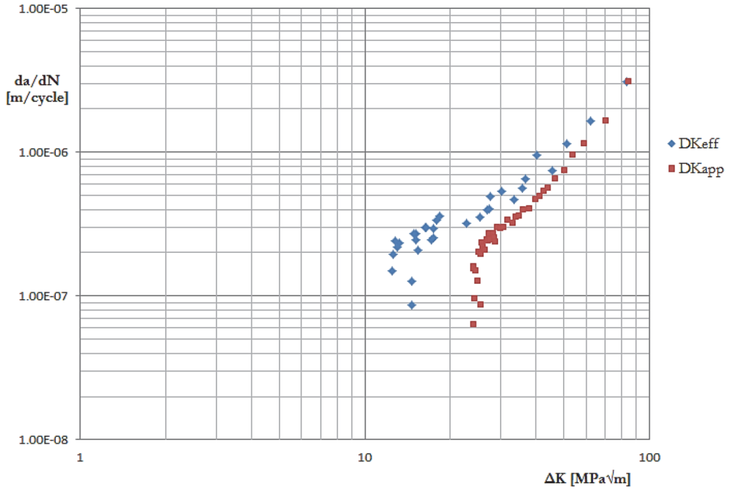


Figure 3: The fatigue crack growth rate function of stress intensity factor range for R = 0.1

Based on the curves in Fig. 3 have been determined the propagation constants corresponding to considered loading. The values are given in Tab. 3.

Specimen type	Thickness [mm]	R-ratio	Paris constants C [m/cycle MPa√m]	Paris constants n	$\Delta K_{th,app}$ [MPa√m]	$\Delta K_{th,eff}$ [MPa√m]
CT	10	0.1	$4 \cdot 10^{-11}$	2.51	22.5	10.5

Table 3: The fatigue crack growth rate constants for constant amplitude loading with R = 0.1

In case of the second sample, after the application of overloading cycle the testing was continued with constant amplitude loading for a total number of 409768 cycles. Throughout the test the compliance technique could not detect an extension of the crack in the plastic deformation zone created by the overload, fig. 4. However, the microscopic analysis revealed that the crack propagated in the plastic deformation zone, fig. 5. Moreover, the character of fatigue crack growth in the plastic zone is totally changed in comparison with the propagation character before applying the overload. This indicates a change of the crack tip shielding mechanisms that govern the fatigue crack propagation. From a combined zone and contact shielding mechanisms was switched to a dislocation crack tip shielding mechanism.

Accepting the crack closure function defined by Elber in the relations (1) and (2), it was made an estimation of the crack opening force corresponding to overloading cycle with maximum force of 20 kN and minimum force of 0.8 kN.

$$U = \frac{\Delta P_{eff}}{\Delta P_{app}} \tag{1}$$

and

$$U = 0.5 + 0.4 \cdot R \tag{2}$$

For the overloading cycle results:

$$0.5 + 0.4 \cdot R_{OL} = \frac{P_{\max,OL} - P_{op,OL}}{P_{\max,OL} - P_{\min,OL}} \tag{3}$$

where R_{OL} is the stress ratio of the overloading cycle.

Solving the Eq. (3) results an estimation value for the crack opening force corresponding to overloading cycle of $P_{op,OL} \approx$ 10.092 kN.

The value of $P_{op,OL}$ is higher than the maximum force of the constant amplitude loading and this could be the reason for why the crack compliance technique could not detect the extension of the crack within plastic deformation zone.

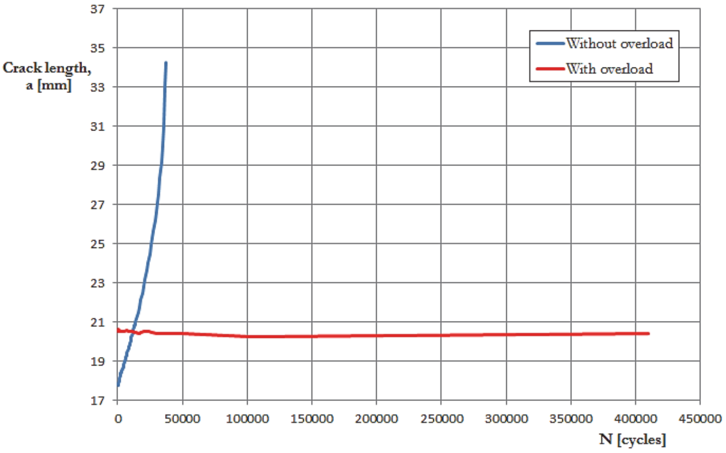


Figure 4: The variation of crack length function of number of cycles.

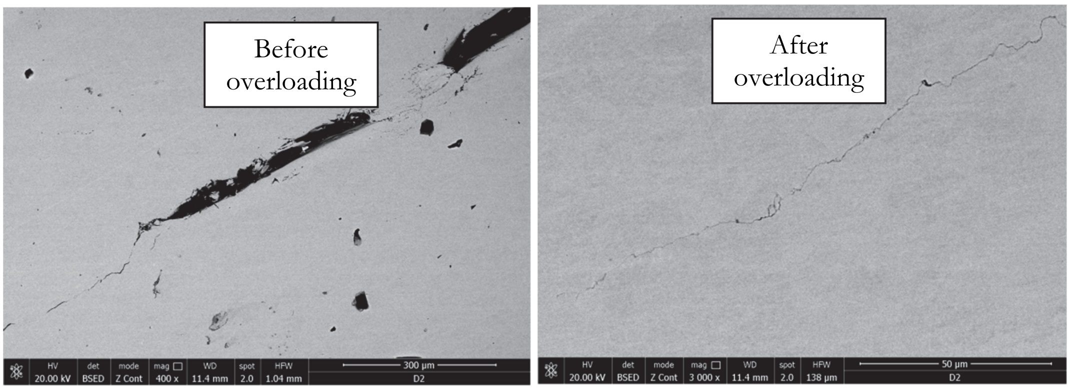


Figure 5: The fatigue crack path before and after overloading

Also, for plane stress state has been highlighted an apparent effect of the overloading on the character of fatigue crack propagation. In Fig. 6 there are givens the variations of fatigue crack growth rate function of the crack length for the two samples overloaded with 26%·$P_{max,CA}$ respectively 82%·$P_{max,CA}$, ($P_{max,CA}$ is the maximum force of constant amplitude loading). Based on the recordings of loading force and respectively COD, (fig. 7), has been determined the crack opening load corresponding to the overloading cycles. The values are given in Tab. 4.

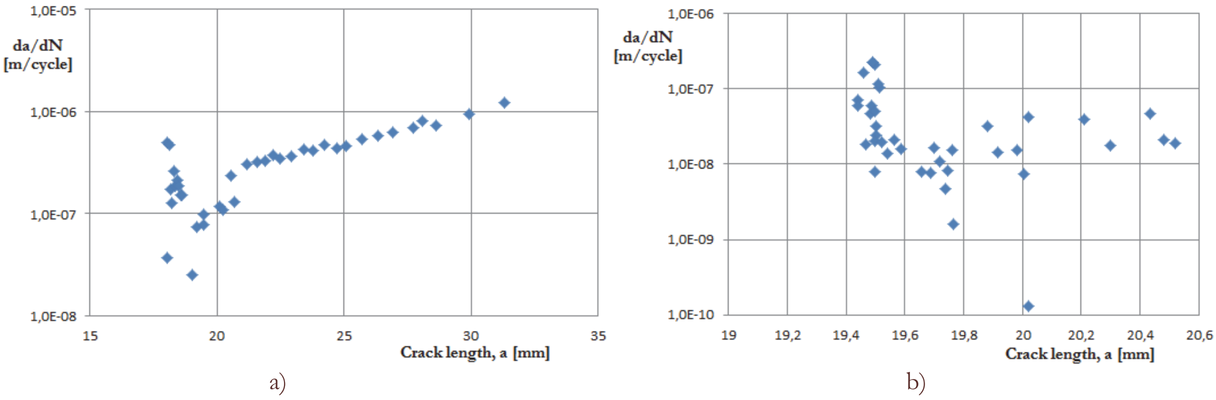
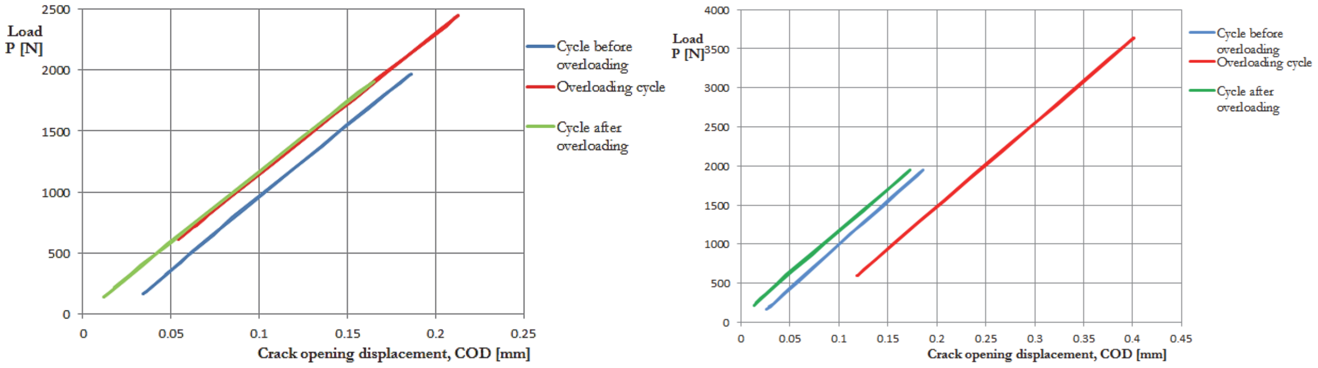


Figure 6: The variation of fatigue crack growth rate function of crack length for: a) 26%$P_{max,CA}$ overloading; b) 82%$P_{max,CA}$ overloading.



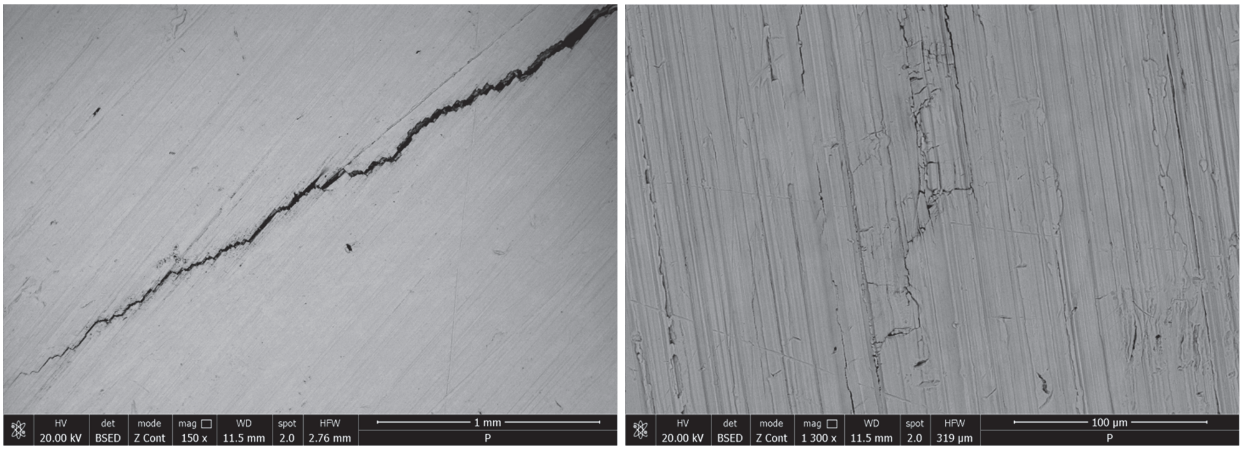
a) b)

Figure 7: The variation curves of load vs. COD for: a) 26%$P_{max,CA}$ overloading; b) 82%$P_{max,CA}$ overloading.

Specimen type	Thickness [mm]	Overloading	Overloading crack opening load, $P_{op,OL}$ [N]
CT_overload26%	2.42	26%$P_{max,CA}$	1950
CT_overload82%	2.43	82%$P_{max,CA}$	2400

Table 4: The crack opening load corresponding to overloading cycles.

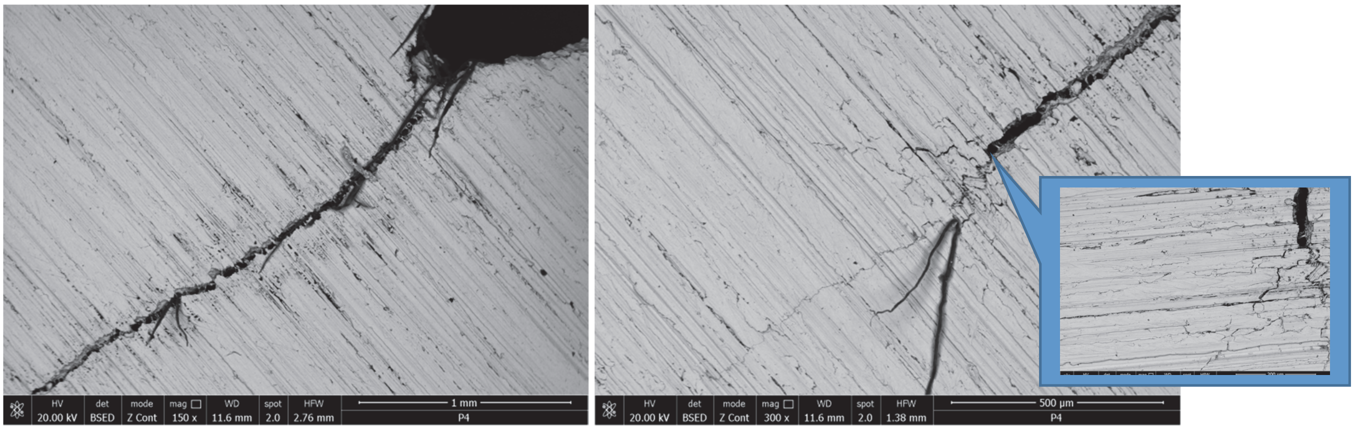
In the first case of overloading, the value of $P_{op,OL}$ is less than the maximum force of constant amplitude loading. This made possible tracking by compliance technique the fatigue crack propagation in the plastic zone and respectively was able to determine the fatigue crack growth rate on the retardation zone given by the overloading cycle, fig. 6.a. Instead, in the second case of overloading the value of $P_{op,OL}$ is greater than the maximum force of constant amplitude loading and therefore the compliance technique could not detect the crack extension in the plastic zone, fig. 6.b. Meanwhile, in both cases the fatigue crack continued to propagate in the plastic zone but with a propagation character totally changed from the propagation mode in front of the overloading, fig. 8-9.



a) b)

Figure 8: The fatigue crack propagation in sample overloaded with 26%$P_{max,CA}$: a) before overloading; b) after overloading.

The fatigue crack propagation in plastic zone was guided by a dislocation crack tip shielding mechanism characterized by branching and interlocking of the crack tip.



a) b)

Figure 8: The fatigue crack propagation in sample overloaded with 82%$P_{max,CA}$: a) before overloading; b) after overloading

CONCLUSION

This paper presents an experimental study on fatigue crack propagation in elastic-plastic material. Is pursued in particular the character of crack propagation in terms of crack tip shielding mechanisms occurring or may occur under certain conditions of crack growth. It is obvious that a change in material behavior (introducing a plastic zone) it falls upon the crack propagation by changing the crack tip shielding mechanisms. The results also indicate that in the plastic zone dominant mechanism is dislocation crack tip shielding. In plane strain condition this mechanism is characterized in particular by interlocking effects of the crack. For plane stress the dislocation crack tip shielding mechanism is manifested by branching and interlocks giving more tortuous character of crack path. In relation to plasticity induced crack closure this mechanism can be considered as an active process that could help to crack extension even if the crack tip is shielded.

Returning to description of Elber about the loading effect on fatigue crack growth and which say that the crack is fully open only for a part of the loading cycle characterized by ΔK_{eff}, than what might happen on the portion between the minimum and opening load? Could this variation to trigger crack tip shielding mechanisms, considering that the crack is surrounded by a plastic deformation field?

The results of this study indicate that the variation $P_{op} - P_{min}$ could determine crack tip shielding mechanisms if P_{op} is high enough. This can meet in area with severe plastic deformations such as those introduced by overloadings.

REFERENCES

[1] James, M.N., Some unresolved issues with fatigue crack closure – measurement, mechanism and interpretation problems, http://www.gruppofrattura.it/ocs/index.php/ICF/ICF9/paper/viewFile/4331/1491;
[2] Christensen, R.H., Fatigue crack growth affected by metal fragments wedged between opening-closing crack surfaces, Appl. Mater. Res., 2(1963) 207-210;
[3] Elber, W., Fatigue crack closure under cyclic tension, Engng. Fract. Mech., 2(1970) 37-45;
[4] Elber, W., The significance of fatigue crack closure, Damage Tolerance in Aircraft Structures ASTM STP 486 (1971) 230-242;
[5] Ritchie, R.O., Mechanisms of fatigue crack propagation in metals, ceramics and composites: role of crack tip shielding, Materials Science and Engineering, A103 (1988) 15-28.
[6] Pippan, R., Hohenwarter, A., Fatigue crack closure: a review of the physical phenomena, FFEMS, 00 (2017) 1-25. doi: 10.1111/ffe.12578;
[7] Mutoh, Y., Korda, A.A., Miyashita, Y., Sadasue, T., Stress shielding and fatigue crack growth resistance in ferritic-pearlitic steel, Materials Science and Engineering A, 468-470 (2007) 114-119. doi: 10.1016/j.msea.2006.07.171;
[8] Weertman, J., Dislocation crack tip shielding and the Paris exponent, Materials Science and Engineering A, 468-470 (2007) 59-63. doi: 10.1016/j.msea.2006.08.128;
[9] ASTM E 647, Standard test method for measurement of fatigue crack growth rates, ASTM, USA.