Effect of short crack on closure behavior in a 304L austenitic stainless steel

K. Vor, C. Sarrazin-Baudoux, C. Gardin, J. Petit
LMPM, UMR CNRS 6617, ENSMA, Chasseneuil du Poitou, France

Abstract

This paper aims to investigate the effect of crack length on closure in a 304L austenitic stainless steel. CT specimens are initially pre-cracked under different constant applied stress intensity factor (SIF) ranges at a load ratio of R = 0.1. Crack closure is detected by means of a back face strain gage at different crack lengths obtained from a progressive electric discharge machining of the crack wake. A numerical tool is developed to analyze the load-displacement curves after signal analysis by means of data filtering. For different applied SIF ranges, the SIF for crack opening K_{op} is shown to increase with the residual crack length ΔC and reaches a steady state K_{op} level for ΔC longer than 1.2 mm. An analytical expression of the evolution of closure versus the crack length is given.

Keywords: crack closure, short cracks, stress intensity factor, stainless steel

1. INTRODUCTION

Crack closure, first experimentally noted by Elber [1], is widely used to rationalize various fatigue crack growth characteristics and has become one of the most intensively studied phenomena associated with fatigue crack growth. However the characterization of closure is mostly based on long crack concept, while only few studies have been performed on short crack. Yet, the behavior of short cracks is shown to be different from that of long cracks. In long crack regime, the fatigue crack growth rate, da/dN, can be characterized by the SIF range, ΔK, as a dominant driving force [2, 3]. On the other hand, when utilizing ΔK for describing short crack growth rate characterization, it usually exhibits a faster growth rate than prediction made under long crack methodology; moreover short cracks even grow below the threshold where long cracks are assumed to be dormant [4]. The high growth rate of physically short cracks has often been attributed to the lack of significant crack closure at the early stage of propagation due to limited length of the crack wake [5, 6]. The effect of short crack and characterization of short fatigue crack growth are, therefore, fairly critical for accurate lifetime prediction of components and structures. Panasyuk et al. [7] also proposed that the behavior of short crack basically depends on the specific features of reversed plastic deformation within the process zone at the crack tip as well as its relationship to the development of crack closure. Therefore, the behavior of short crack has a close relationship with the plastic wake because it causes crack closure, i.e., crack surfaces can locally come into contact along the entire crack length or in specific crack section. Breat et al. and Petit et al. [8, 9]

have demonstrated that closure of short cracks depends on the crack length. These authors have indicated that closure of a physically short crack generally increases with crack growth and merges with that of long crack.

Therefore, the objective of this paper is to explore the evolution of closure as a function of the residual plastic wake length on CT specimens pre-cracked at constant applied SIF range in such a very ductile material as 304L austenitic stainless steel.

2. EXPERIMENTS

2.1. Material

The material used in this study is 304L austenitic stainless steel. The 0.2% yield stress is 220 MPa, the maximum tensile strength is 555 MPa, and the elongation at failure is approximately 60%. The chemical composition of this material is shown in Table I.

Table I. Chemical composition of the employed 304L stainless steel

C	Mn	Si	S	P	Ni	Cr	Mo	Cu	N_2
0.029	1.86	0.37	0.004	0.029	10	18	0.04	0.02	0.056

2.2. Specimen

Normalized CT50 specimens are used in this study. The stress intensity factor can be calculated by using the following equation proposed by AFNOR [10]:

$$K = \frac{P \times Y}{BW^{1/2}} \tag{1}$$

where P is the applied load, B and W are respectively the specimen's thickness and width. Y is a form factor depending on the geometry of the specimen and the crack length a. For CT specimen, Y is expressed as follows:

$$Y = \frac{(2+\alpha)\left(0.886 + 4.64\alpha - 13.31\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right)}{(1-\alpha)^{3/2}} \tag{2}$$

where $\alpha = \dfrac{a}{W} > 0.2$

2.3. Pre-cracking and residual crack length preparation

A through thickness pre-cracking was performed on CT specimens with a constant applied ΔK and a load ratio of $R = 0.1$ at room temperature with a loading frequency of 20 Hz. Four different levels of ΔK were investigated. The tests were performed manually by shedding the applied load with crack growth. The load shedding intervals were chosen so that the maximum ΔK fluctuation was smaller than 1%. After each load step, the crack length was measured optically on both sides by a travelling microscope mounted in front of the specimen. The alignment of the specimen was optimized to keep a maximum difference in crack length observed on both sides lower than 0.1 mm. Each crack length was determined as the mean value of the measurement on both sides. The pre-cracking was carried until the crack length reaches a ratio $a/W \approx 0.5$ then crack wake was progressively electric discharge machined (M1, M2, etc) through the crack path (see Fig. 1). This created a 0.3 mm wide gap between the surfaces and produced different residual lengths of the plastic wake ΔC. The final shortest length ΔC_f was about 0.1 mm. Crack closure was measured at each step of the procedure.

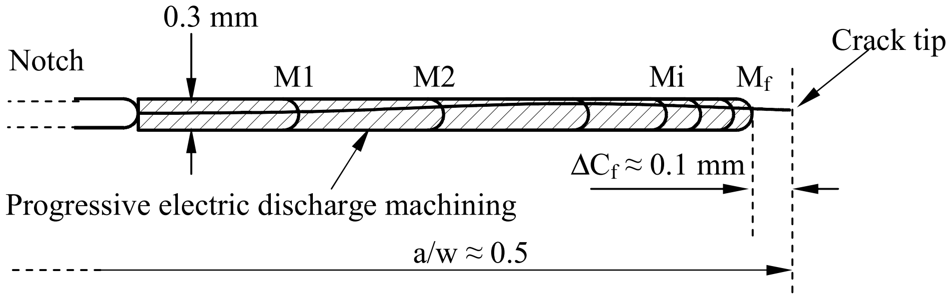

Fig. 1 : Electric discharge machining to produce residual plastic wake lengths on a pre-cracked CT specimen

3. CLOSURE MEASUREMENT

Crack closure originally observed by Elber [1], is the leading mechanism in explaining the influence of different factors, such as stress ratio R effect and load interaction phenomena. This author introduced the following effective driving force concept:

$$\Delta K_{eff} = K_{\max} - K_{op} \tag{3}$$

where K_{max} is the SIF at maximum load and K_{op} is the SIF at opening load.

This knowledge of ΔK_{eff} is a key parameter for the study of the crack propagation and leads to an improvement in estimating the structure's fatigue life time. Accordingly, many experimental methodologies have been proposed to characterize the value of K_{op} as precisely as possible, while the compliance method is widely used due to its experimental simplicity. In this paper, to improve the graphic method commonly used to identify the opening load P_{op} on the compliance curve as plotted by XY plotter, a numerical tool was developed to detect P_{op} from the compliance curve acquired digitally during the tests.

3.1. Data acquisition

Numerical data acquisitions of the compliance curves (applied load P vs. δ strain given by a "back-face" strain gage) were carried out by slowing down the testing frequency to 0.2 Hz. The final data sets are consisting in 250 points per cycle.

3.2. Numerical method for the calculation of P_{op}

The determination of crack opening P_{op} from the loading cycle of P vs. δ is illustrated in Fig. 2a as proposed by Elber [1] but this is not always easy and obvious. Kikukawa et al. [11] introduced the concept of differential compliance curve P vs. δ' which enables easier determination of P_{op} (Fig. 2b). The slope of the linearity of the curve P vs. δ is assumed to be the compliance value χ corresponding to fully open crack configuration and it is used to calculate δ' for each loading cycle. For the sake of a more precise solution, the P vs. δ' curves were regrouped together from five successive cycles of the same measure.

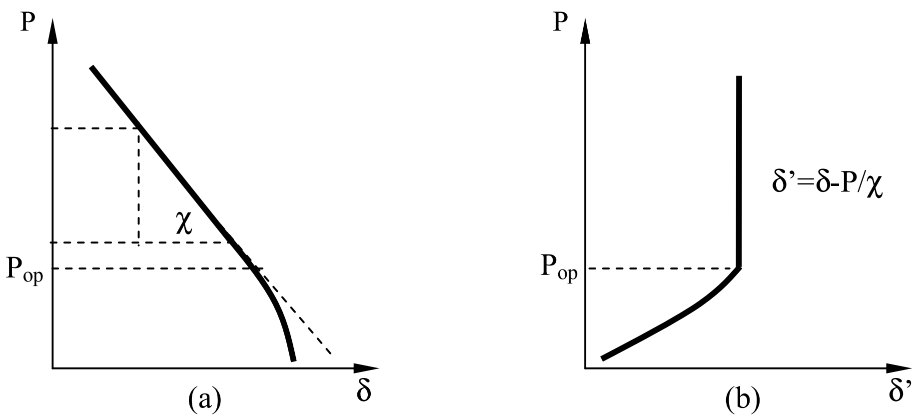

Fig. 2 : Typical curves of (a) compliance and (b) differential compliance

3.2.1. Data filtering

As the data can be affected by any kind of noise during acquisition, a data filtering is needed before performing the signal analysis to obtain P vs. δ' curves as clean as possible. A data smoothing in two steps was performed on the P vs. δ and on P vs. δ' data sets. These methods provide efficient data filtering as illustrated in Fig. 3.

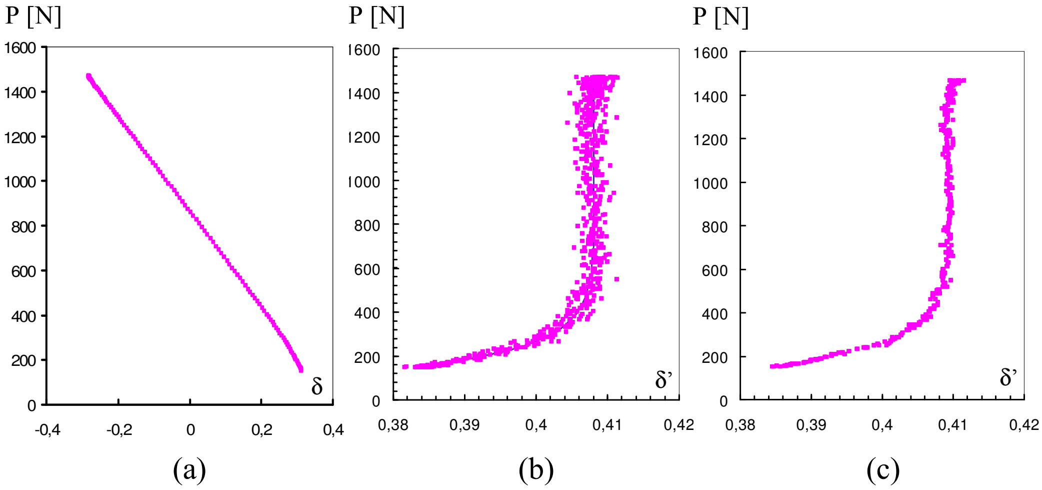

Fig. 3 : Examples of the compliance curves obtained from a 304L CT specimen pre-cracked at $\Delta K = 6$ MPa√m with residual crack length $\Delta C = 10$ mm (a) P vs. δ; (b) P vs. δ' and (c) P vs. δ' after data filtering

3.2.2. Numerical determination of P_{op}

In order to calculate automatically the value of P_{op}, a numerical function was identified from fitting to the final filtered data of P vs. δ' (Fig. 3c) which is expressed below :

$$P = B \ln[f(\delta')] + P_o \tag{4}$$

where B and P_o are the fitting constants.

P_{op} is identified as the intersection point between a vertical line δ'_{op} offsetting 5% of (δ'_{moy} - δ'_{min}) and the fitting function (4). δ'_{op} is denoted as:

$$\delta'_{op} = \delta'_{min} + 0.95\,(\delta'_{moy} - \delta'_{min}) \tag{5}$$

where δ'_{min} and δ'_{moy} are respectively the minimum and the asymptotic values of δ' as illustrated in Fig. 4.

Thus
$$P_{op} = B \ln[f(\delta'_{op})] + P_o \tag{6}$$

A typical data set obtained after the filterings when the crack is relatively long is illustrated in Fig. 4a. In such case, the determination of P_{op} is quite obvious. The dispersion is low compared to the global compliance variation. For short crack, the determination of P_{op} is more critical. When the crack is shorter than 0.3 mm, the variation of compliance is very small. The data scattering , even after filtering, still remains important (Fig 4b). Sometimes, the diagrams can not be interpreted. But in most cases, these diagrams (as that presented in Fig. 4b corresponding to a short crack of 0.1 mm) allow an acceptable calculation of P_{op} even in such critical experimental conditions. An illustration of the application of this method is given in the following for 2D short crack experiments on the 304L austenitic stainless steel.

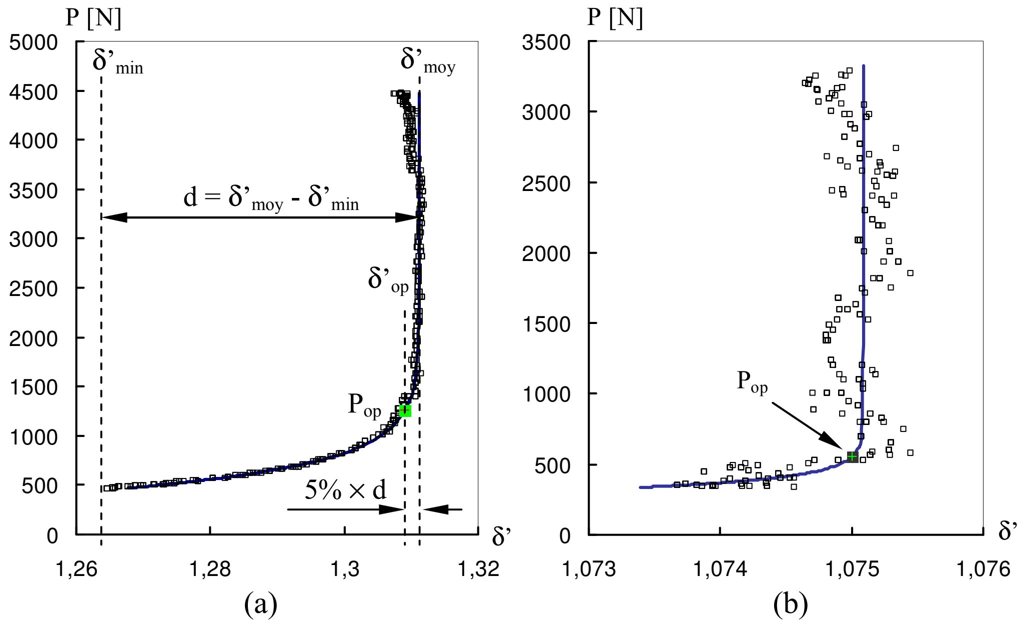

Fig. 4 : Examples of the determination of P_{op}.
(a) ΔK=18 MPa√m, ΔC = 10 mm. (b) ΔK=15 MPa√m, ΔC = 0.1 mm

4. RESULTS AND DISCUSSIONS

Four ΔK levels of pre-cracking were applied to CT specimens which were then electric discharge machined to produce different lengths of residual crack wake varying from 15 mm to the shortest length around 0.1 mm. Closure measurements were performed approximately for fourteen different residual crack lengths on each specimen. The results are illustrated in Fig. 5. Two distinct regimes of closure can be seen. One corresponds to long crack regime where K_{op} reaches a steady state level $K_{op.steady}$ independent of residual crack length ΔC and the second one corresponds to short crack regime where K_{op} depends on ΔC. For all levels of applied ΔK, in the long crack regime where ΔC is longer than $\Delta C_{cr} \approx 1.2$ mm, the levels of $K_{op.steady}$ are shown to increase with the increasing applied ΔK. On the other hand, in the short crack regime where ΔC is shorter than ΔC_{cr}, crack closure decreases as expected with decreasing length of residual crack wake. This phenomenon can be related to the reduction in length of crack wake along the crack path which causes less premature contact during unloading [4, 5]. Since the plastic wake plays an important role in the behavior of closure, consequently the plastic wake behind 1.2 mm from the crack tip does not contribute to the crack closure. Therefore, in the design of 304L stainless steel structures, special attention should be taken into account when the crack is shorter than 1.2mm in length where closure is strongly reduced. This implies a reduction in the lifetime of the structures.

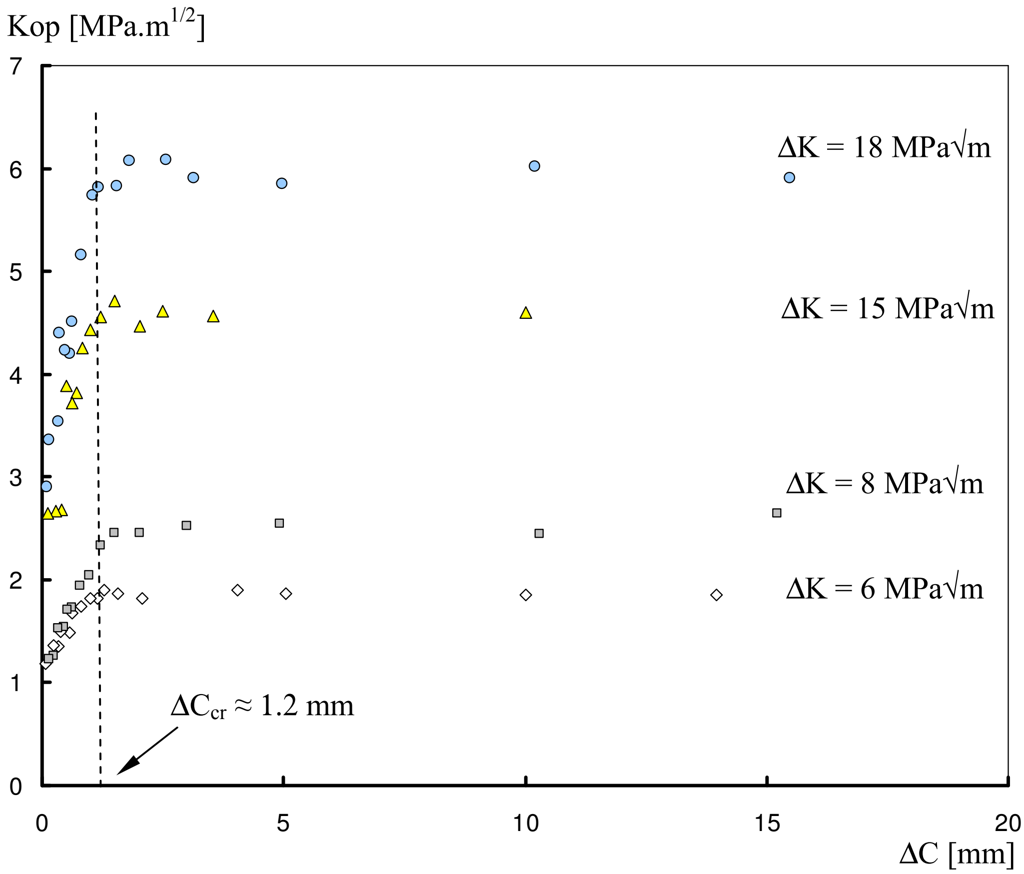

Fig. 5 : Evolution of K_{op} versus residual crack length ΔC after electric discharge machining on CT specimens pre-cracked at different SIF ranges, R=0.1.

For further design applications, an empirical model has been identified from the obtained experimental results in order to predict the behaviour of crack closure by taking into account the crack length and the applied SIF range. An exponential function is used to represent this evolution, as expressed below:

$$K_{op} = \left(K_{op.steady} - K_{\min}\right)\left(1 - e^{-\beta\Delta C}\right) + K_{\min} \qquad (7)$$

where $K_{op.steady}$ is a linear function of ΔK as illustrated in Fig. 6.

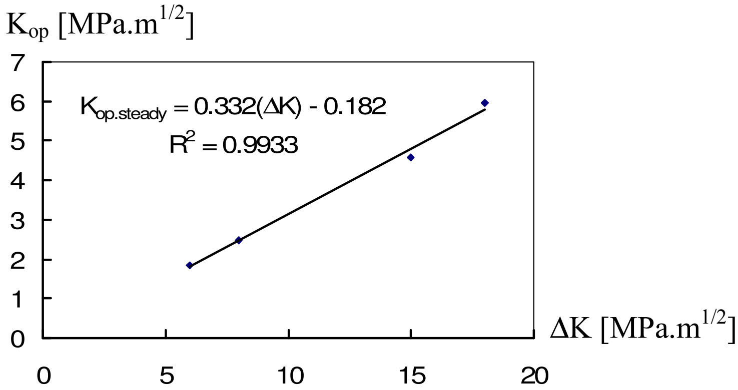

Fig. 6 : Evolution of K_{op} in steady state as a function of applied ΔK .

and β is obtained by best fitting with the experimental results (Table II):

Table II. Values of β obtained from different levels of ΔK

ΔK [MPa.m$^{1/2}$]	6	8	15	18
β	2.99	1.82	2.4	2.79
β_{mean}		2.5		

The mean value of β is used in the following for all applied SIF ranges.

Thus $$K_{op} = (0.332\Delta K - 0.182 - K_{\min})(1 - e^{-2.5\Delta C}) + K_{\min} \quad (8)$$

By using a 5% offsetting methodology, the domain of closure affected by short crack ΔC_{cr} can be easily calculated by the model, as illustrated in Fig. 7.

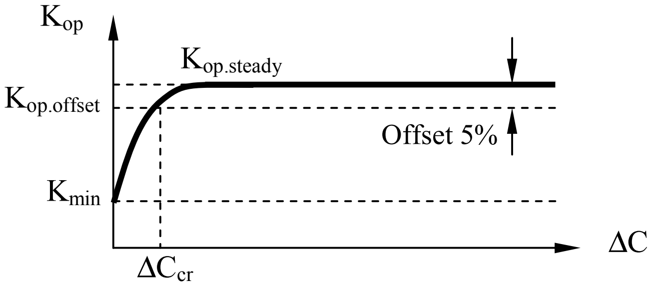

Fig. 7 : Determination of the domain of short crack ΔC_{cr} by the model

where $$K_{op.offset} = K_{min} + 0.95\,(K_{op.steady} - K_{min}) \quad (9)$$

From equation (7), it comes: $$\Delta C = -\frac{1}{\beta}\ln\left(1 - \frac{K_{op} - K_{\min}}{K_{op.steady} - K_{\min}}\right) \quad (10)$$

$$\Delta C_{cr} = -\frac{1}{\beta}\ln\left(1 - \frac{K_{op.offset} - K_{\min}}{K_{op.steady} - K_{\min}}\right) = -\frac{1}{2.5}\ln(1 - 0.95) = 1.198\ \text{mm} \quad (11)$$

The domain of short crack ΔC_{cr} calculated by the model is very consistent with the estimation made on the experimental results as mentioned above. Fig. 8 illustrates the good agreement between experiments and the prediction of the equation (8).

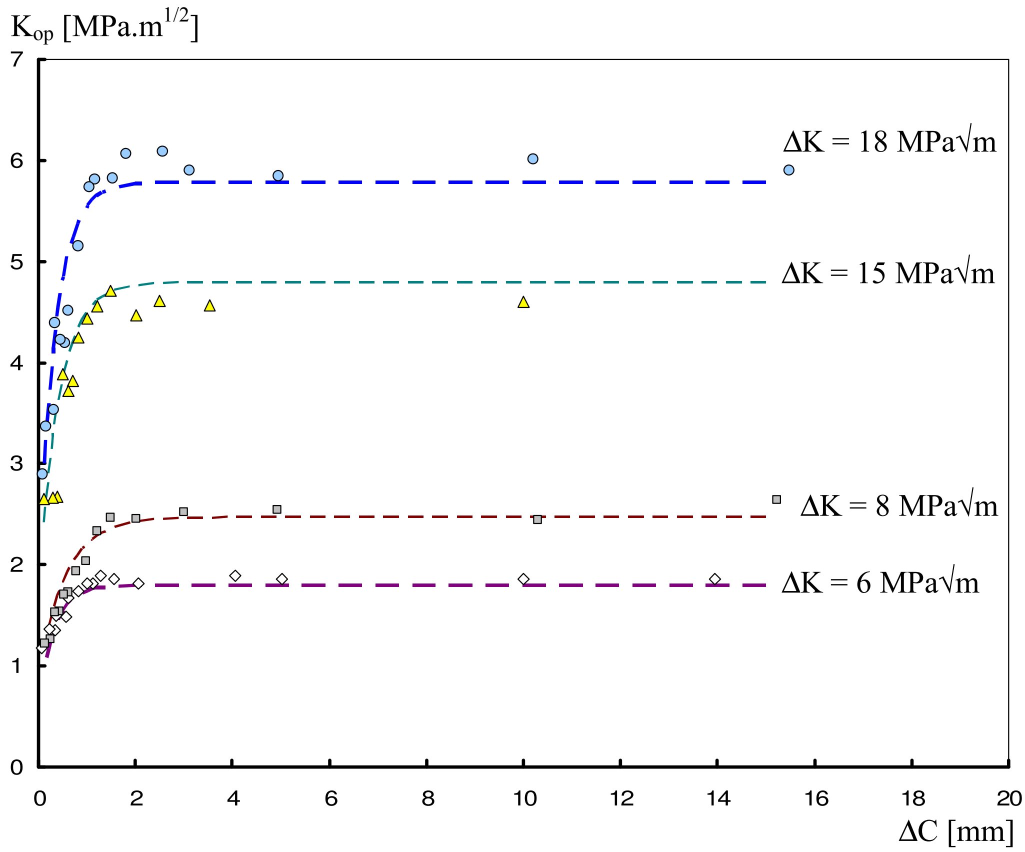

Fig. 8 : Comparison of closure behavior between current model and previously obtained experimental results
(Dot for experimental data, dashed lines for modeling)

5. CONCLUSIONS AND PERSPECTIVES

Crack closure evolution with respect to the residual crack length through different levels of applied SIF range at load ratio of $R = 0.1$ was characterized by a numerical method developed by the authors. The proposed method for data acquisition and analysis of compliance variation, allows crack closure detection and K_{op} measurement for 2D crack having a length as short as 0.1 mm.

The results obtained on the 304L austenitic stainless steel are as follows:

- At constant applied ΔK amplitude, the closure contribution of long crack $K_{op.steady}$ is shown to be independent of crack length. Moreover, $K_{op.steady}$ varies linearly versus ΔK.

- In the short crack regime where crack is shorter than 1.2mm, K_{op} decreases rapidly from the constant asymptotic value $K_{op.steady}$ when the crack length is progressively reduced.

An empirical model is proposed for describing K_{op} with respect to ΔC and applied ΔK.

Ongoing experiments on short crack propagation at constant ΔK are scheduled in order to characterize the closure with respect to the crack propagation. These tests will complete the current study on the role of crack closure.

The influence of the loading ratio R will also be investigated.

6. REFERENCES

[1] W. Elber, Fatigue crack closure under cyclic tension, Eng Fract Mech, 2 (1970) 37 – 45

[2] G. R. Irwin, Analysis of stresses and strains near the end of a crack traversing a plate, Journal of Applied Mechanics 24 (1957) 361 – 364.

[3] P. C. Paris and G. C. Sih, Fracture toughness testing and its application, ASTM STP 381, 1965, pp. 30 – 83

[4] S. Peason, Investigation of fatigue crack in commercial aluminum alloys and the subsequent propagation of very short cracks, Engng. Fract. Mech. 7 (1975) 235 – 247

[5] A. J. McEvily, On the growth of small/short fatigue cracks, JSME Int J. 32 (1989) 181 – 191

[6] T. Christman and S. Suresh, Crack initiation under far-field cyclic compression and the study of short fatigue cracks, Engng. Fract. Mech. 23 (1986) 953 – 964

[7] V.V. Panasyuk, O. YE. Andreykiv, R.O. Ritchie, O.I. Darchuk, Estimation of the effects of plasticity and resulting crack closure during small fatigue crack growth, Int. J of Fracture 107 (2001) 99 -115

[8] J. L. Breat, F. Mudry and A. Pineau, Propagation and non propagation of short fatigue cracks at a sharp notch, Fat. Engng. Mater. Structure 6 (1983) 315-327

[9] J. Petit and A. Zeghloul, On the effect of environment on short crack growth behaviour and threshold, Mech. Engng. Publications, London, 1986, pp. 163-177

[10] AFNOR A03-404, Pratique des essais de vitesse de propagation en fatigue, Association Française de Normalisation, June 1991

[11] M. Kikukawa, M. Jono and S. Mikami, Journal of the Society on Materials. Japan, Vol. 31 (1982) 438-487