NUMERICAL SIMULATION OF CRACK GROWTH IN HIGH PRESSURE COMPONENTS

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ABSTRACT

Finite element simulations of the propagation of small cracks were performed using crystal plasticity constitutive equations in order to have a better understanding of closure/opening phenomena induced by the plasticity confined at the crack tip. Two numerical methods can be applied to simulate the crack growth :

- A node release technique performed after a time of stabilisation of the cyclic plasticity at the crack tip in order to have an estimation of the Stress Intensity Factor at crack opening, Kop, taking into account the plastic wake zone,
- A numerical coupled analysis using a cohesive zone modelling under cyclic loading in order to develop a coupled predictive approach of the crack growth.

In this study, our interest will be devoted to the uncoupled technique. For the case of a single crystal, exhibiting a cube symmetry, we analysed :

- The material anisotropy effect on the energy release rate G,
- The effect of the crack growth direction on Kop in the crystallographic axis,
- The “short cracks” effect on the threshold Kop.

1 INTRODUCTION

In blading components, a large proportion of service life is taken up in initiating and growing surface or near surface short cracks through the Stage I regime in fatigue, that is when the crack length is small compared to the scale of the crack tip plasticity.

Such fatigue cracks driven by mechanical and thermal stresses can lead to the catastrophic failure of a component. This is why short cracks behaviour in Ni-base superalloys has received considerable attention.

In order to have a better understanding of the short crack behaviour in anisotropic materials such as single crystal superalloys, two different methods of finite element modelling are developed and applied to analyse the crack growth. In this paper, we focused our interest on the uncoupled method.

2. DESCRIPTION OF THE APPLIED METHODOLOGY

The mechanical effects induced by the crack closure play a very important role with respect to the crack propagation rate. An applied overload increases the size of the current plastic zone at the crack tip but, in parallel, it modifies significantly the conditions for the subsequent crack closure or, consequently for its opening (figure 1) (Elbert [1]).

The Linear Fracture Mechanic takes into account the plasticity confined at the crack tip through Kop, introduced in the Paris Law:

$$\frac{da}{dN}=C\left(\Delta K_{eff}\right)^{n} \qquad \text{with} \qquad \Delta K_{eff}=K_{\max}-K_{op}$$

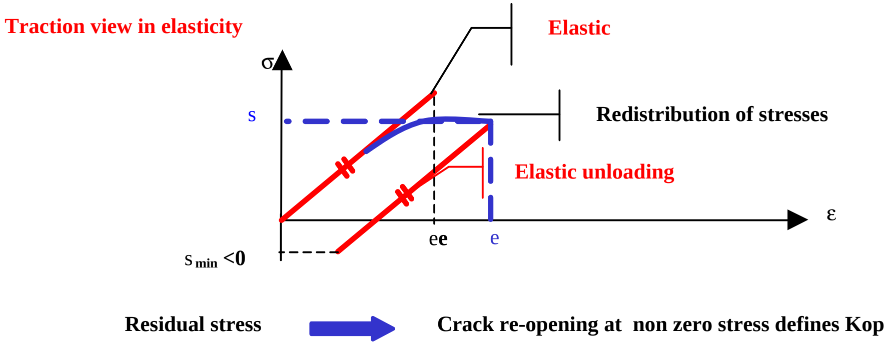


Figure 1 : Determination of Kop in elastoplasticity.

A classical way for the numerical simulation of the crack closure/opening consists of uncoupled cyclic plasticity analyses at a given crack length (Newman [2], Fleck [3]). The arbitrary crack growth (not correlated with any crack growth rate prediction) is simulated by the node release method, which consists to impose a zero force to the node located at the crack tip after to reach a stabilised state of the cyclic plasticity (Sansoz [4], Prigent[5]).

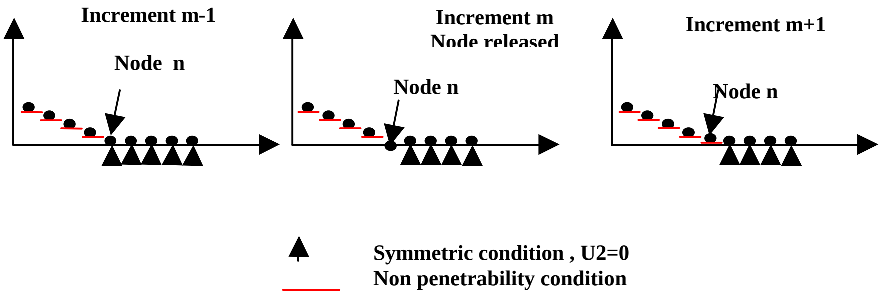


Figure 2 : Release node technique.

For the present study, the finite element analyses are based on a mode I fatigue crack growth in a smooth specimen using the generalised plane strain hypothesis, with a typical mesh shown in figure 3 below :

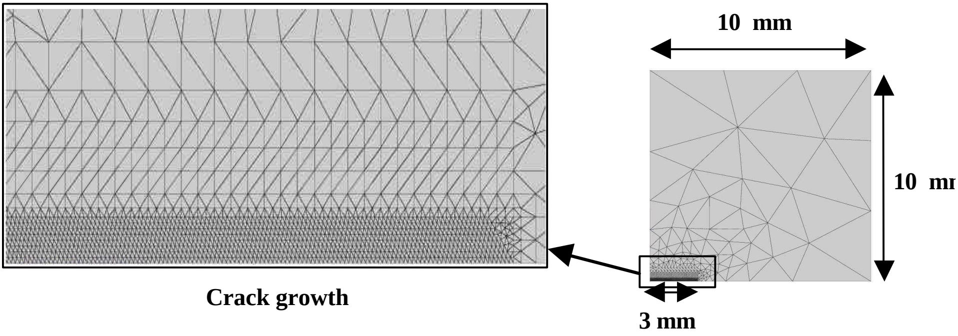


Figure 3 : Type of mesh used.

The material is a single crystal superalloy, exhibiting the cube symmetry, with an application at high temperature and characterised by an elastoviscoplastic constitutive model based on slip systems (Nouailhas and Culie[6], Cailletaud [7]).

3. RESULTS

First, we show, in elasticity, for anisotropic materials exhibiting the cube symmetry, that the energy release rate G depends on the material anisotropy. The following figure 4 gives the evolution of G for different directions of the crack growth front in the crystallographic axis (q is the angle between the crack growth direction and [100] orientation).

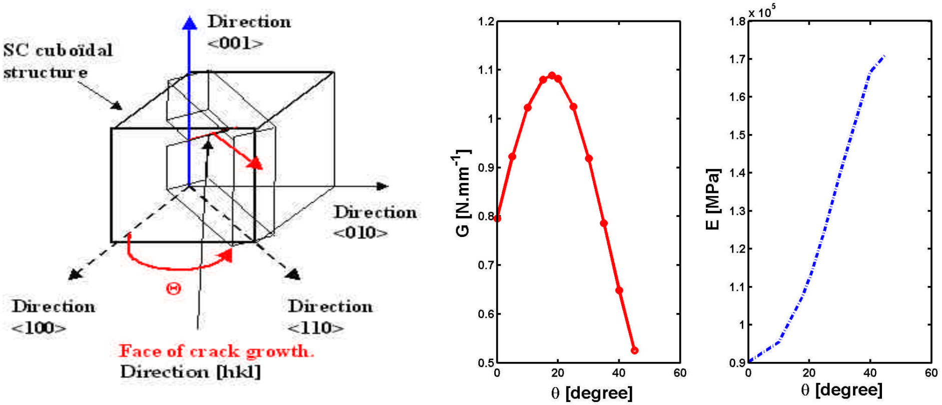
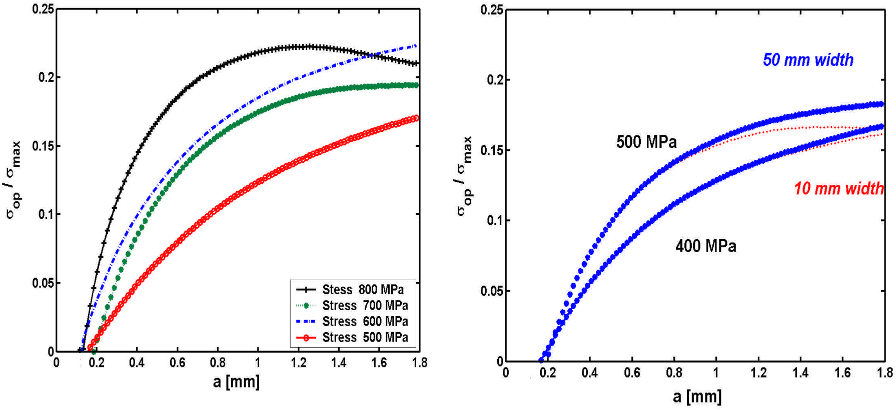


Figure 4 : Evolution of G for different directions of the crack growth.

We observe that G is a function of the anisotropy material. Moreover it seems that there are no simple relations between the Young modulus E and G evolving with the angle q .

Figure 5a shows the evolution of the crack opening stress as a function of the crack length for different load levels. We can notice that the more the stress increases, the more the threshold stabilises rapidly. Plasticity seems to play an important role in the stabilisation of the threshold. For short cracks, with lengths lower than 1.5 mm, a significant dependence of the threshold with the applied load is observed. This phenomena could be induced by the relatively small size of the plastic zone at the crack tip in comparison with the size of the crack. Once the crack has propagated and can be considered as a long ones (i.e a > 1.5mm), the opening level stabilisesas it is commonly observed.

As it can be shown in figure 5b, the opening threshold is also sensitive to the edge effect due to specimen dimensions.



a   b

Figure 5 : Evolution of opening threshold stress for different load levels (a) and edge effect (b).

We reported in the figure 6 below the opening threshold versus the crack length for notches with different geometries. Several remarks can be formulated :

- The plasticity on notch tip has an effect that decreases when the crack length increases,
- At the beginning of the cyclic loading, the opening threshold increases with the plasticity generated by the notch,
- For a crack length reaching 1.2 mm, the effect of plasticity due to notch becomes negligible compared to the plasticity generated by crack tip which gradually becomes prevalent.

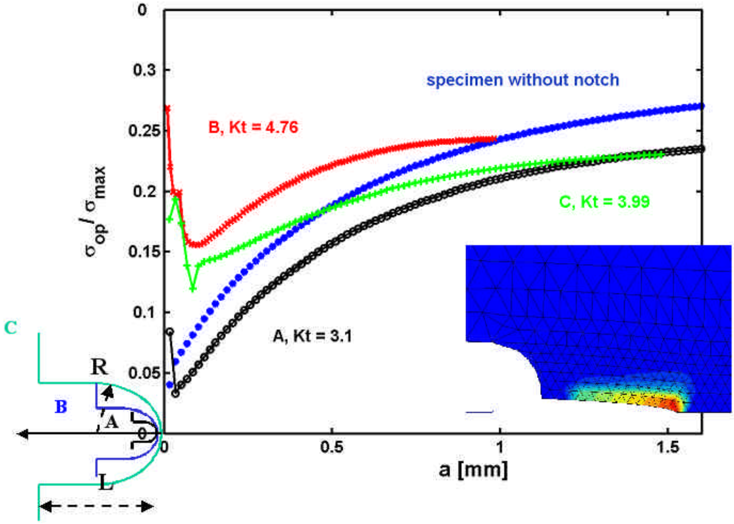


Figure 6 : Evolution of the opening threshold for notches with different geometries.

The phenomena described above show that the history of the plasticity generated by the notched specimen is forgotten after a certain crack length and only the plasticity confined at the crack tip plays an important role in the crack growth process.

CONCLUSION AND FURTHER DEVELOPMENTS

Single crystal materials are not often studied in terms of crack growth simulations and of the associated closure/opening effects (Forest[8]). One of the objectives of this study was to analyse the interaction of such effects with the wake plastic zone and the current directional localisations at the crack tip induced by slip plasticity.

Another specific objective of our work is the development of a coupled numerical approach, allowing a free crack propagation without any external control. For this coupled analysis, we intent to establish a specific damage model of fatigue crack growth (De-Andres[9], Nguyen[10] and Yang[11]) with the following specificities:

- To simulate the continuous crack growth during low cycle and high cycle fatigue by means of cohesive elements,
- To couple the crack growth simulation with the cyclic plasticity and damaging processes ahead of the crack tip.

REFERENCES

[1] Elbert, “ Fatigue crack closure under cyclic tension”, Engng Frac. Mech., 2, pp. 37-45, 1970.

[2] Newman, “Finite element analysis of crack growth under monotonic and cyclic loading”, Cyclic Stress-Strain and plastic Deformation Aspect of Fatigue Crack Growth, ASTM STP 637, American Society of Testing and Materials, pp. 56-80, 1977.

[3] Fleck, « Finite element analysis of plasticity-induced crack closure under plain strain condition”s, Engng Frac. Mech., 25, pp. 441-449, 1986.

[4] Sansoz, « Propagation des petites fissures de fatigue dans les zones de concentration de contraintes dans le superalliage N18 », Thesis of Ecole des Mines de Paris, 2000.

[5] Nouailhas and Culie, “Development and application of a model for single crystal superalloy”, ASME, MD 26, AMD-121, New York, 151, 1991.

[6] Cailletaud, « Une approche micromécanique phénoménologique du comportement inélastique des métaux », Thèse de doctorat d’Etat, 1987.

[7] Prigent, « Modèle de propagation de fissure à haute température avec intéraction fatigue-fluage-oxydation, Thèse de l’Ecole Nationale des ponts et Chaussées, 1993.

[8] Flouriot, Forest, Rémy, “Strain localization phenomena under cyclic loading : application to fatigue of single crystals”, Comp. Mat. Sc., 26, pp. 61-71, 2003.

[9] De-Andres and al., “Elastoplastic finite element analysis of three-dimensional fatigue crack growth in aluminium shaft subjected to axial loading”, Int. J. Of Solids And Struct., pp. 2231-2258,1999.

[10] Nguyen and al., “A cohesive model of fatigue crack growth”, Int. J. Of Fract., pp. 351-369, 2001.

[11] Yang and al., “A cohesive zone model for fatigue crack growth in quasibrittle materials”, Int. J. Of Solids And Struct., pp. 3927-3944, 2001.